

Final Scientific/Technical Report

Title: Implementation of the Polarized HD target at the Thomas Jefferson National Accelerator Facility

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Introduction and brief summary

This is a brief summary of the achievements of the grant in the technical, manpower training and publications areas. For more detailed technical accomplishments during the whole period of the grant, refer to the section below “Detailed Technical Results”.

The original goal of this proposal was to study frozen spin polarized targets (HD target and other technologies) and produce a conceptual design report for the implementation of such a target in the HALL B detector of the Thomas Jefferson National Accelerator Facility (JLab). During the first two years of the proposal, we came to the conclusion that the best suited target for JLab was a frozen spin target and helped with the design of such a target. We have not only achieved our original goal but have exceeded it by being involved in the actual building of the target. The main reason for this success has been the hiring of a senior research associate, Dr. Oleksandr Dzyubak, who had more than 10 years of experience in the field of frozen spin polarized targets. He was a resident at the DOE laboratory (JLab) from June 2002 until August 2006, and, has been instrumental in getting the target group at JLab to work on designing and building a polarized frozen spin target for HALL B.

The current grant has allowed the USC nuclear physics group to strengthen its role in the JLab collaboration and make important contribution to both the detector development and the scientific program. We are currently within six months of having a working target in HALL B ready for experiments.

Scientific merit

The strong scientific merit of the polarized target at JLab has been stressed by the JLab international Program Advisory Committee (PAC). The combination of a state of the art polarized target with the JLab polarized gamma beam makes of the Cebaf Large Acceptance Spectrometer (CLAS) a unique detector system that can perform critical double polarization experiments.

Since 2002, the PAC has approved four experiments needing the polarized target. USC is an integral part of the following four approved experiments:

- E-02-112 Search for Missing Nucleon Resonances in Hyperon Photoproduction;
- E03-105: Pion Photoproduction from a Polarized Target.
- E-04-102 (updated E-01-104): Helicity Structure of Pion Photoproduction;
- E-05-012 Measurement of polarization observables in eta-photoproduction

The JLab PAC stated in his report:” ... *The PAC strongly encourages the timely development of the frozen spin target ... A new polarized target is required. A transverse-polarization capability is essential. The PAC sees these experiments as an important part of the laboratory’s program.* “

The laboratory management, following the recommendation of the PAC for the timely development and implementation of a frozen spin target, did allocate equipment funds for buying the polarizing magnet and building the cryostat. The polarizing magnet was delivered at JLab in 2004 and was tested by USC. It not only met but exceeded the specifications. The cryostat has been assembled in fall 2006, and is being currently tested and will be available for the commissioning this spring.

Progress and Status of the Project

This project really took off in June 2002 when our target expert (Dr. Dzyubak) was hired. After extensive studies of the different technologies, in 2003, USC and Jlab reached the conclusion that it was more practical to pursue the proven “traditional frozen spin design” as opposed to the new HD frozen spin being developed at the Brookhaven National Laboratory.

A preliminary design called for a target with a typical diameter of 1.5 cm and a length of 5 cm able to use three different target materials Butanol (4C9HOH), Ammonia (N3H) and Lithium Hydride (LiH). By the end of 2003, a first design of a dilution refrigerator was finished and cost estimates were made. A first bid for the polarizing magnet was received and the JLab management requested funds to start ordering parts for tests and prototyping. A polarizing magnet (5.0 Tesla at 1.0 K) was bought by JLab and tested by USC. USC also designed and tested several prototypes of holding magnets (0.3 Tesla at 50 mK)

Dr. Dzyubak completed the design and simulation of the 0.5 Tesla holding magnets that will enable to increase the run time between re-polarizations by a factor of two. The prototyping and field measurements for the solenoid under real working conditions, inside the cryostat at 1.0 K were completed early 2004. The 5.0 Tesla polarizing magnet was delivered early 2004. To get the maximum values during the polarization process, the polarizing magnet field homogeneity over the target volume should be better than 100 ppm. As part of the commissioning of the polarizing magnet, Dr. Dzyubak designed and manufactured the installation necessary to measure the field map with an NMR probe. We were able to achieve accuracy better than 10 ppm! Field mapping was completed and showed that the polarizing magnet is very reliable and can be used with a large variety of target materials.

By Fall of 2005, JLab had allocated funding for the construction of the cryostat. The goal was to have a working target by end of 2006 and to be able to run the approved experiments by spring of 2007.

Manpower training (post-doc and graduate student)

The proposal called for hiring a relatively senior target expert as a Post-doctoral fellow and our search was successful in 2002 and we were lucky to attract and hire Dr Oleksandr Dzyubak. Dr. Dzyubak had more than 10 years of experience with all aspects of the frozen spin target and has been a major contributor to this project. Together with our graduate student Nicolas Recalde, Dr Dzyubak visited the Brookhaven target group and reported early on the status of the HD target. This resulted in the decision to pursue the conventional frozen spin target technology at JLab. Dr. Dzyubak has been involved with the design and testing of almost all the key components of the target (polarizing magnet, holding magnet, target geometry, target material, NMR, etc.). He has been instrumental in not only coming up with a technical evaluation of the HD implementation but the design, prototyping and testing of an actual target. This was a positive outcome far exceeding the goals of the original proposal and has helped the USC group become key player at a National Laboratory. The extension of the grant allowed us to contribute to the building of the target and be a spokesperson on an approved experiment using the target. Dr Dzyubak expertise and contacts were indispensable to achieve this working target.

Dr. Dzyubak is now working as a Medical physicist at the Mayo clinic in Minnesota.

We had one Hispanic graduate student involved with the project. Nicolas Recalde worked closely with Dr. Dzyubak on the design and testing of important component of the target. He defended his MS thesis in August 2003 ("*Holding Magnet System for JLab Hall-B Frozen Spin Polarized Target*") on the target project. Polarized targets required very advanced skills and it is hard to keep good students for a long time. Nicolas was offered a highly paid job as a Medical Physicist at George Town Hospital in Washington DC. He is trying to pursue his PhD with our group as a full time working professional.

Whenever possible, our post-doc and graduate student were encouraged to make presentation at scientific or working meetings.

Publications and Talks

Technical Publications

- 1) O. Dzyubak, C. Djalali, S. Strauch and D. Tedeschi, "Magnet and beam studies for the JLab Hall-B Frozen Spin Polarized Target", published by World Scientific (2006), Proc. XI-th International Workshop on Polarized Sources and Targets, November 14-17, 2005, Tokyo, JAPAN.
- 2) O. Dzyubak, C. Djalali, N. Recalde, and D. Tedeschi, "Design of internal superconducting holding magnet for the JLab Hall-B Frozen Spin Polarized Target", Nucl. Instr. Meth. In Phys. Res. A 526, 132, (2004).
- 3) C.D. Keith, M.L. Seely, O. Dzyubak, "Design of a Frozen Spin Target for CLAS", GDH-2004, Proceedings

of the Third International Symposium on the Gerasimov-Drell-Hearn Sum Rule and its Extensions, June 2-5, 2004, p.201-205.

4) C. Djalali, O. Dzyubak, and D. Tedeschi, "Studies of dipole magnets for transversal holding magnetic field for the JLab Hall-B Frozen Spin Polarized Target", 9th Inter. Workshop on Polarized Solid Targets & Techniques, October 27 - 29, 2003, Physikzentrum of Bad Honnef, Germany.

5) C. Djalali, O. Dzyubak, and D. J. Tedeschi, "Magnetic Field Studies for the JLab Hall-B Frozen Spin Target", Polarized Sources & Targets (PST-2003), September 22-26, 2003, Novosibirsk, Russia.

6) O. Dzyubak, "Frozen Polarized Target for JLAB photon experiments", American Physical Society Meetings, April 5-8, 2003, Philadelphia, Pennsylvania.

7) N. Recalde, O. Dzyubak, C. Keith, and M. Seely, "Holding Magnet System for JLAB Hall-B Frozen Polarized Target", American Physical Society Meetings, April 5-8, 2003, Philadelphia, Pennsylvania.

8) N. Recalde, O. Dzyubak, C. Keith, and M. Seely, "Prototypes of Holding Magnet System", South Carolina Academy of Science, Proceedings of the 76th Annual Meeting, March 20-21, 2003, Clemson, South Carolina.

9) O. Dzyubak, "Frozen Polarized Target for JLAB photon experiments", South Carolina Academy of Science, Proceedings of the 76th Annual Meeting, March 20-21, 2003, Clemson, South Carolina.

10) A. Byelyayev, O. Dzyubak, O. Lukhanin, "Simulations of Q-meter for precise measurements of proton polarization for the JLAB Frozen Spin Target", JLab CLAS Notes, CLAS-NOTE 2006-002, Newport News, VA, USA, 2006.

11) A. Byelyayev, O. Dzyubak, O. Lukhanin, "Polarized Target technologies developed at National Science Center Kharkov Institute of Physics and Technology (Kharkov, Ukraine) and their possible applications for the FROST project at JLAB Hall-B", JLab CLAS Notes, CLAS-NOTE 2006-003, Newport News, VA, USA, 2006.

12) O. Dzyubak, C. Djalali, and D. Tedeschi, "GEANT simulation of beam heat deposition in Hall-B Frozen Spin Polarized Target", JLab CLAS Notes, CLAS-NOTE 2005-015, Newport News, VA, USA, 2005.

13) O. Dzyubak, C. Djalali, and D. Tedeschi, "Precise field map measurements for Hall-B Frozen Spin Target Polarizing Magnet", JLab CLAS Notes, CLAS-NOTES 2004-023, Newport News, VA, USA, 2004.

14) O. Dzyubak, C. Djalali, and D. Tedeschi, "Notes about Holding Magnet System for the Hall-B Frozen Spin Polarized Target", JLab CLAS Notes, CLAS-NOTES 03-002, Newport News, VA, USA, 2003.

Technical talks

1) O. Dzyubak, C. Djalali, S. Strauch and D. Tedeschi, "Magnet and beam studies for the Jlab Hall-B Frozen Spin Polarized Target", XI-th International Workshop on Polarized Sources and Targets, November 14-17, 2005, the University of Tokyo, Tokyo, Japan.

2) A. Belyaev, O. Dzyubak, O. Lukhanin, "Simulations of Q-meter for precise measurements of proton polarization for the JLAB Frozen Spin Target", FROST Working Group at CLAS Collaboration Hall B Meeting, November 3-5, 2005, Newport News, VA, USA.

3) A. Belyaev, O. Dzyubak, O. Lukhanin, "Polarized Target technologies developed at National Scientific Center of Ukraine (KIPT, Kharkov) and their possible applications for the FROST project at JLAB Hall-B", FROST Working Group at CLAS Collaboration Hall B Meeting, November 3-5, 2005, Newport News, VA, USA.

- 4) O. Dzyubak, C. Djalali, D. Tedeschi, "Medical applications of polarization techniques developed for Nuclear and Particle Physics", South Carolina Academy of Science, 77th Annual Meeting, March 15-16, 2005, Rock Hill, South Carolina.
- 5) O. Dzyubak, S. Dzyubak, "Low level measurements of radioactive residuals as spin-offs from High Energy and Particle Physics to the Medicine and Nutrition Quality Control Service", South Carolina Academy of Science, 77th Annual Meeting, March 15-16, 2005, Rock Hill, South Carolina.
- 6) O. Dzyubak, "GEANT simulation of beam heat deposition in Hall-B Frozen Spin Polarized Target", Hadron Spectroscopy Group at CLAS Collaboration Hall B Meeting, December 4, 2004, Newport News, VA, USA.
- 7) O. Dzyubak, "Short holding solenoid for Hall-B Frozen Spin Target", Hadron Spectroscopy Group at CLAS Collaboration Hall B Meeting, October 15, 2004, Newport News, VA, USA.
- 8) O. Dzyubak, "Precise field map measurements for Hall-B Frozen Spin Target Polarizing Magnet", Hadron Spectroscopy Group at CLAS Collaboration Hall B Meeting, June 20, 2004, Newport News, VA, USA.
- 9) O. Dzyubak, "Hall-B polarizing magnet field measurements with high precision", Jefferson Lab Hall-B Staff Meetings, May 10, 2004, Newport News, VA, USA.
- 10) O. Dzyubak, "0.5 Tesla internal holding magnet system for JLAB Hall-B Frozen Spin Target", Real Photon Working Group at CLAS Collaboration Hall B Meeting, February 7, 2004, Newport News, VA, USA.
- 11) O. Dzyubak, "Forces acting on conductors of 0.3 Tesla holding magnet system in self-induced magnetic field", Real Photon Working Group at CLAS Collaboration Hall B Meeting, November 14, 2003, Newport News, VA, USA.
- 12) O. Dzyubak, "Force Calculations Update", Real Photon Working Group at CLAS Collaboration Hall B Meeting, September 13, 2003, Newport News, VA, USA.
- 13) O. Dzyubak, "Investigation of a series of dipole magnets for transversal holding magnetic field for the Jlab Hall-B Frozen Spin Polarized Target", Real Photon Working Group at CLAS Collaboration Hall B Meeting, June 30, 2003, Newport News, VA, USA.
- 14) O. Dzyubak, "Results of magnetic field measurements of the first prototypes of the holding solenoid and bedstead", Real Photon Working Group at CLAS Collaboration Hall B Meeting, December 14, 2002, Newport News, VA, USA.
- 15) O. Dzyubak, "Primary results of magnet field measurements of the first prototypes of the holding solenoid and bedstead", Real Photon Working Group at CLAS Collaboration Hall B Meeting, November 16, 2002, Newport News, VA, USA.
- 16) O. Dzyubak, "Notes about Holding Magnet System for the Hall-B Frozen Spin Polarized Target", Real Photon Working Group at CLAS Collaboration Hall B Meeting, November 16, 2002, Newport News, VA, USA.
- 17) O. Dzyubak, "OPERA(TOSCA) Holding Solenoid calculations for Hall-B Frozen Spin Polarized Target", Real Photon Working Group at CLAS Collaboration Hall B Meeting, October 18, 2002, Newport News, VA, USA.
- 18) O. Dzyubak, "Frozen spin mode Polarized Target for Hall-B", Real Photon Working Group at CLAS Collaboration Hall B Meeting, August 9, 2002, Newport News, VA, USA.

Detailed technical results

Requirements for a new polarized target at Jefferson Laboratory

The JLAB Hall-B large acceptance spectrometer (CLAS) is an almost 4π detector [1] that is able to operate with both electron and tagged photon beams using a variety of targets. Considerable data have been collected using an electron beam and polarized targets [2-5]. The target [6] was longitudinally polarized using a pair of 5.0 Tesla superconducting Helmholtz coils and was located 0.57 m upstream of the center of the CLAS detector. The on-axis bore of the magnet was 20.0 cm in diameter that provided a 55° open aperture for particles scattered into the forward cone. The target cell, a cylinder with 2.0 cm in diameter and 2.0 cm long, was immersed in a liquid He bath maintained at approximately 1.0 K by the ^4He evaporation refrigerator described in ref. [7-8]. The target material chosen was ammonia because of its high resistance to radiation damage [9-10].

The main disadvantage of the existing target is that it only could be located out of the CLAS detector far away (about 3 feet) from the geometrical center whereas the new generation of the experiments requires the target being located inside the detector and right in the center. Five proposals have been approved by the JLab Program Advisory Committee [11-15].

After taking into account all of these requirements, a reasonable choice for a polarized target is to use the “Frozen Spin” mode which implies the separate use of both an “external” polarizing and an “internal” holding superconducting magnets. In this mode, the target material should be polarized outside the CLAS detector at $B = 5.0$ Tesla and $T = 1.0$ K. After the maximal polarization is achieved, the cryostat is turned to the “holding” mode at $B = 0.5$ Tesla and $T = 50$ mK and moved inside the CLAS detector. Since the new target will be used only in photo-nuclear experiments, in addition to ammonia, alcohols such as butanol or propandiol could also be used as a target material. At temperature $T = 50$ -60 mK and holding field $B = 0.5$ Tesla, the expected relaxation time for both alcohols and ammonia is about $t = 10$ days (200-300 hours)[16-21].

Some equipment and instrumentation from the previous polarized target [6] will be used; however, we need a new dilution refrigerator, a polarizing magnet and holding magnets. The 5.0 Tesla superconducting polarizing magnet has been ordered [22]. The design work on the $T = 50$ mK dilution refrigerator is underway and it will be built on site at Jefferson Lab.

The purpose of this work is to produce an optimal design of “internal” superconducting holding magnet for longitudinally and transversally polarized targets. The purpose of this project is to design such a facility that could meet the demands of new experiments.

The first proposal [11] had taken the same target cell geometry as the previous design of polarized target used for the CLAS detector[6]. However after preliminary Monte Carlo simulations it had been shown that if such dimensions are to be taken ($D=20$ mm; $L=20$ mm), then to have acceptable statistics, the required beam consumption should be unacceptably high (more than 150 days) and could not be approved by PAC. For this reason University of South Carolina Nuclear Physics group suggested to enlarge the length of the target by factor 2.5 (or even 5.0!) that leads to the geometrical dimensions of the target cell $D=20.0$ mm and $L=50.0$ mm. Following Monte Carlo simulations proved that a target with $L=50.0$ mm is the best optimal choice. In fact, $L=100.0$ mm overloads the CLAS detector data acquisition systems.

Choice of best polarized target

Availability and evaluation of HD-Target

Experts from the University of South Carolina Nuclear Physics group visited the Brookhaven National Lab and Orsay HD polarized target facilities to study the status and availability of the equipment and manpower for implementing an HD-target as a Polarized Target candidate for JLab HALL-B CLAS

The HD-facility the LEGS Spin Collaboration consists of:

- 1) Production cryostat (T = 4.2 - 2.0 K, H = 2.0 Tesla, NMR-system TE-signal)
- 2) Transfer cryostat (T = 5.0 -- 6.0 K, B = 0.7 Tesla)
- 3) Polarizing cryostat (B=15.0 Tesla T = 17 mK; homogeneity better than 1%.)
- 4) In-beam cryostat (B= 0.7 Tesla, T= 1.3 K)
- 5) Storage cryostat (B = 2 Tesla, T = 4.2 K)

Results of the consultation with LEGS experts:

**Required Cell geometry*

Cylinder D = 25 mm, L=50 mm

Amount of HD -- 1 Mol (3 gm solid HD)

Background -- 3 gm solid HD + 20% Al by weight (2050x50 mkm wires)

**Expected polarization and decay time with a beam of 10^7 photons/s (after 10 days)*

-with the "Old" in-beam cryostat (B=0.7 Tesla @ T= 1.3 K)

P_H = 70% and T_H = 13 days (312 hours)

P_D = 17% and T_D = 36 days (864 hours)

-with "new" in-beam cryostat (B= 1.0 Tesla @ T= 0.2 K)

P_H = 80% and more than T_H = 30 days (720 hours)

P_D = 50% and more than T_D = 100 days (2400 hours)

**Cost estimate if JLab duplicates the BNL system*

Production cryostat	\$40 K
Transfer cryostat	\$125 K
Polarizing cryostat	\$700 K
In-beam cryostat	\$400 K
Storage cryostat	\$50
Electronics, NMR	\$60 K
Cryo-other	\$50 K
Contingency	\$200 K

Total : \$1625 K

**Cost estimate if JLab uses parts of the BNL system*

Transfer cryostat	\$125 K
In-beam cryostat	\$400 K
Storage cryostat	\$50
Electronics, NMR	\$60 K
Cryo-other	\$50 K

Total: \$685 K

This is an expensive option and might not work right away since it is a new technology that still needs to be proven at BNL.

Availability and suitability of conventional polarized targets.

Experts from the University of South Carolina Nuclear Physics group visited the Jefferson National Lab and University of Virginia conventional polarized target facility to study the status and availability of the equipment and manpower.

After long lasting studies, the summary was reported on the meeting of the Real Photon Working Group (August 9, 2002). "Frozen spin mode, Polarized target for HALL-B. Status" by M. Seely (JLab staff), Ch. Keith (JLab staff), D. Crabb (UVA), O. Dzyubak (USC)

Possible polarized target

- The geometry

The polarized target will be used in the “Frozen Spin” mode. To realize such a mode, a polarizing and a holding magnet are needed. The target material will be polarized outside of the CLAS detector and then moved inside the detector during measurements. Therefore the geometrical position of target inside the CLAS mini-torus is very important and two options were considered:

- power down the CLAS detector while the 2.5 T Polarizing Magnet is on, or,
- move the cryostat back and forth through the Polarizing Magnet. In this case after the polarization is achieved, the polarizing magnet moves aside and the cryostat moves into the detector.

- The cryostat

It was early on decided that the JLab target group should build an entirely new cryostat. The system should have the enough cooling power for polarizing butanol as target material. Butanol has a density of 0.81 g/cc @ 20C and a target volume of $V=4.42 \text{ cm}^3$ would require a microwave power consumption of 1-2 mW/g @ 2.5T/0.5K and 20-40 mW/g @ 5.0T/1.0K. This implies that the fridge should provide a cooling power better than 8.0 mW @ 2.5T/0.5K and 160.0 mW @ 5.0T/1.0K.

- The polarizing magnet

A quote from American Magnet Inc. for a 5.0 T magnet seemed reasonable with specifications more that adequate for the desired polarized target. This commercial 5T magnet was ordered by Jlab and later tested by USC.

- The holding magnet

In the “frozen Spin Mode”, the polarization of the target is maintained by a holding magnet. The homogeneity of the magnetic field is critical for the life time of the polarization. Several prototypes were designed, built and tested. The simplest one was for a longitudinally polarized target and consisted of a superconducting solenoid made of two layers of wires (diameter of 0.1 mm) carrying a current of 12.0 Amps and producing a field of field 0.29 Tesla. The first test done by USC achieved 0.3 T field before quenching. The quench did not damaged the solenoid. The solenoid was then modified for NMR measurements to test field homogeneity (see below).

- The pumping system

Hall-B has enough pumping capacity providing the 3000 m³/hour which is needed for the "frozen spin mode".

- The target material

Several different material were studied as candidates for the target:

- Butanol($\text{C}_4\text{H}_9\text{OH}$) -- 0.81 g/cc -- 0.135 (10/74) dilution factor
- Ammonia (N_3H) -- 0.70 g/cc -- 0.176 (3/17)
- Lithium Hydride(LiH) -- 0.78 g/cc -- 0.143 (1/7)

Butanol and ammonia can be used with a standard cryostat design. LiH requires additional cryostat improvements.

-The microwave generator

There are two options for the polarizing procedure:

-- 140 GHz @ 5.0 Tesla

-- 70 GHz @ 2.5 Tesla

requiring powers at resonance cavity of

8.0 mW 70 GHz @ 2.5 Tesla

160.0 mW 140 GHz @ 5.0 Tesla

The choice of 140 GHz @ 5.0 Tesla mode was dictated by the fact that all necessary parts for the generator were available at JLab and UVA.

- Q-meters

The JLab polarized target group had four Q-meters, which can be used for our "frozen spin" target.

- The control systems (Panels)

We needed to build control systems for the:

- vacuum system
- ^3He and ^4He pumping system
- low temperature
- magnetic field
- microwave
- polarization signal monitoring
- computer programs (Q-meters, control users interfaces etc.)

- Cost Estimate

Following the design and options described above, it was shown that a functional polarized target suited for the physics goals could be built at a much lower cost than the HD option with the advantage of being a “conventional and already proven” technology. No surprises are expected in this approach!

In terms of manpower, four experts have been involved M. Seely and Ch. Keith from JLab, D. Crabb from UVA and O. Dzyubak from USC.

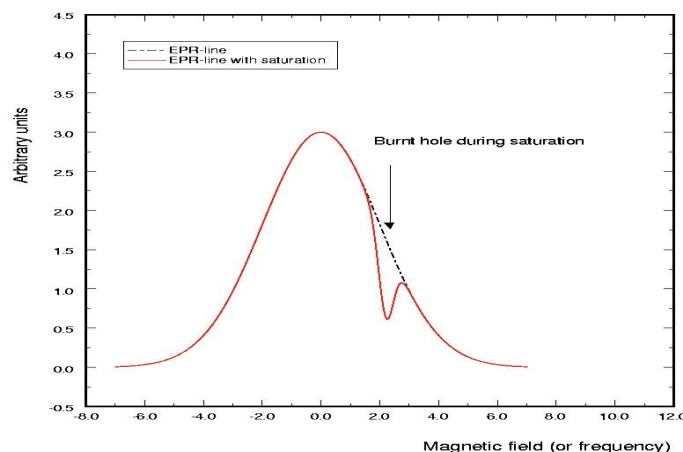
Polarizing Magnet System

Requirements

In frozen spin mode, the polarizing magnet should provide the optimal polarizing conditions during the polarization process, rapidly recover the optimal polarizing conditions during repolarizing cycles and be precisely reproduce a homogeneous field over the target area.

Hall-B Frozen Spin Target will use a dynamic way to enhance a polarization of target nuclei (DNP technique). To realize the DNP technique, polarized targets use paramagnetic impurities (unpaired electrons) embedded in a host target material (alcohols with Cr-V, irradiated ammonia, irradiated lithium, etc.). DNP process is defined by concentration and behavior of those paramagnetic centers (shown by EPR-line shape and width, spectral diffusion rate, etc.). Thus a choice of a target material (material plus paramagnetic centers) defines DNP process which eventually impacts the experimental setup and in particular the polarizing magnet field requirements.

Inhomogeneous broadened EPR-line



For the chosen target material, the DNP process is defined by concentration and properties of paramagnetic centers:

1) relation between the width σ of the EPR-line and the nuclear Larmor frequency ω_I ;

$\sigma \ll \omega_I$ -- solid effect;

$\sigma > \omega_I$ -- differential solid effect, dynamic cooling, cross relaxation;

2) rate of spectral diffusion of a saturated transition inside the broad EPR-line;

low rate -- differential solid effect, cross relaxation;

high rate -- dynamic cooling.

The paramagnetic centers (PC) of all conventional materials have an EPR-line width σ , which is “broad” as compare with the corresponding Zeeman nuclear frequencies ω_I .

Polarization properties of materials with the broad EPR-line

1) Function “polarization value vs magnetic field” has a dispersion shape.

2) Distance between peaks of max polarization $\Delta H = H_+ - H_-$ is defined by DNP mechanism and does not depend on a type of polarizable nuclei.

$$\Delta H \approx \sigma \text{ (EPR-line width)}$$

3) Value of polarization enhancement does not depend on the type of nuclei but EPR-line properties.

Conventional materials

Material	EPR-line Width, —	Proton Larmor Frequency, 5.0 T —, Mhz	Spectral Diffusion	DNP	Distance between Polarization peaks — H, Oe	PC Concentration x 10 ²⁰ cm ³	Reference
Propanediol with EHBA-Cr-V	750 Mhz (270 Oe)	212	High	Dynamic Cooling	270	1.2 – 2.5	Kharkov, [1]
Irradiated ammonia	200 Mhz (70 Oe)	212	Low	Differential Solid effect	90	~ 1.0	Kharkov, [2,3]
Ethandiol, propanediol with Cr-V	230 Mhz (82 Oe)	212	High	Dynamic Cooling	82	0.1 – 0.5	Dubna, [4]

1) A.A. Belyaev et al., Journ. Applied Spectroscopy, 68(4), 2001, p.623.

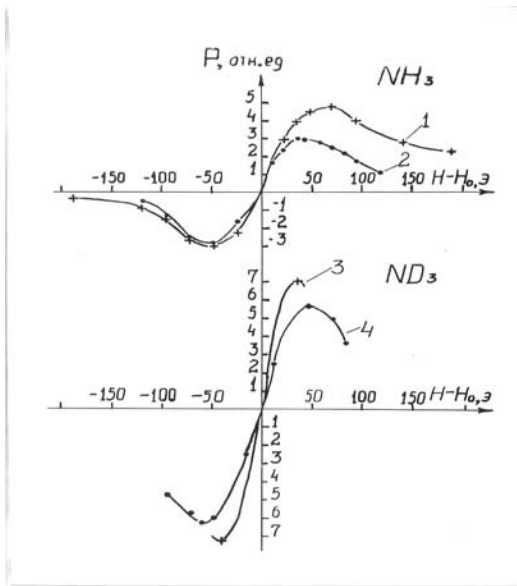
2) O. Dzyubak, PhD Thesis.

3) A.V. Vertij et al., Sov.Phys.Dokl. 35, 1990, p.899.; A.A. Belyaev et al., AIP Conf. Proc. 187, 1989, p.1336; V.P. Androsof et al., ibid, p.1346;

4) N.C. Borisov et al., Sov.Phys.JETP, 60(6), 1984, p.1291.

Experimental measurements of polarization value vs polarizing field.

To prevent polarization “leak”, a field should be kept under resonance conditions within a tolerance of about 5.0 Oe !



Polarization vs polarizing field (Oe) (O. Dzyubak, Thesis, 1989)

Field homogeneity requirements (5.0 Tesla polarizing magnet)

To get the maximum values during the polarization process, the magnet field homogeneity over the target volume (cylinder of $D = 15.0$ mm and $L = 50.0$ mm) should be better than 100 ppm !

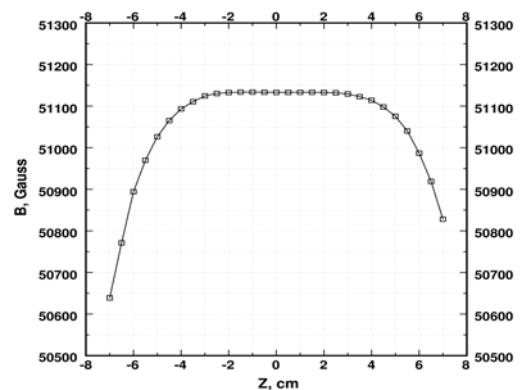
To recover the optimal polarizing conditions is critical for the “Frozen Spin mode”. It requires “many” repolarizing cycles during the run period. Thus before each repolarizing cycle, we should be able to quickly recover optimal field conditions within tolerance: 100 ppm !

The polarizing magnet was bought from Cryomagnetics, Inc. and the company provided the field map only along the central axis with a 5.0 mm step which was too coarse for our purpose.



Field map along central axis

(Cryomagnetics, Inc.)



Motivation for field map measurements.

Cryomagnetics, Inc. only provided a field map along the central axis. It is critical to determine the field

homogeneity over the whole target volume. The field map accuracy should be better than 10 ppm. After setting up the control system field limits setpoints, we needed to know how precisely the control system can recover the optimal polarizing field during repolarizing cycles. During repolarizing cycles, we need to know what tolerance in the positioning the target cell (cryostat tail) relative to the geometrical center of the polarizing magnet we can afford.

Classification of methods for magnetic measurements.

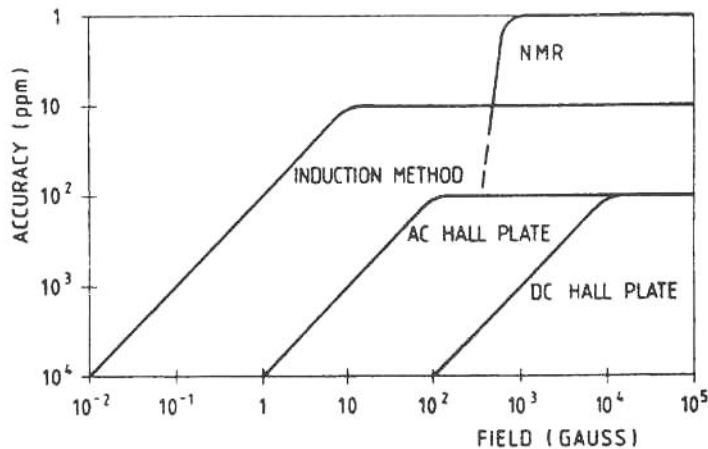


Fig. 1 Measurement methods: accuracies and ranges

K.N. Henrichsen (CERN, 1998) has shown the following accuracy ranges:

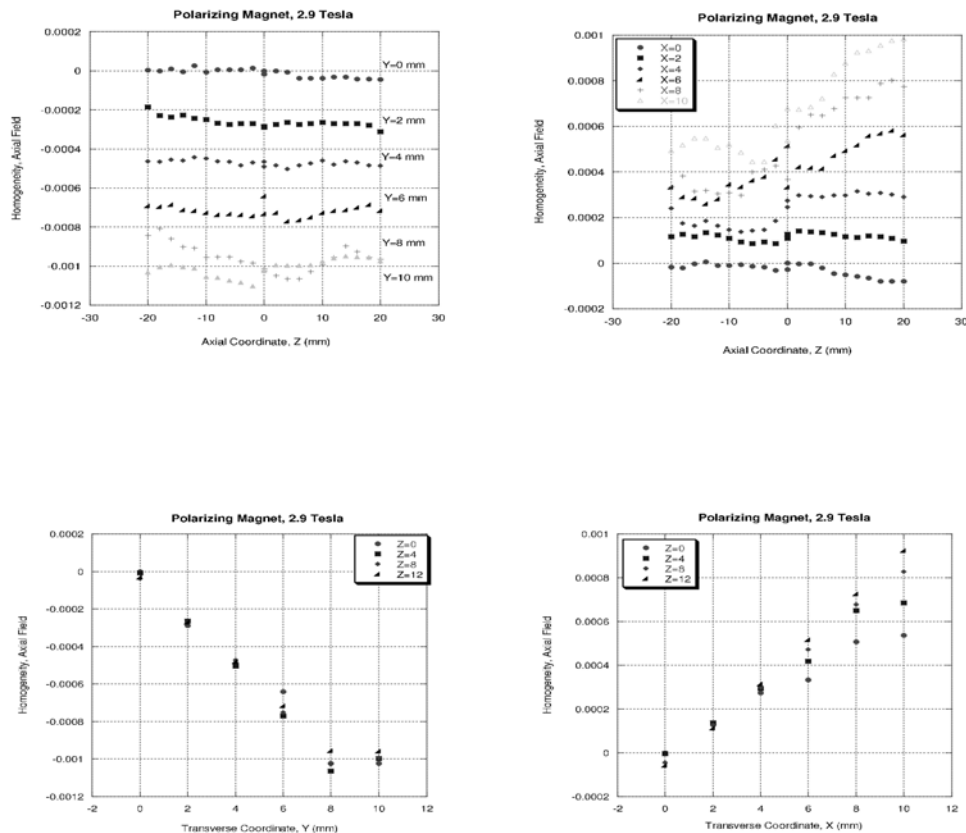
Hall-probe – below 100 ppm;

NMR-probe – 1 ppm.

The NMR-technique is very sensitive to the magnetic field homogeneity but cannot be used for measurements in fields with high drop off. In contrast to that, the Hall-probe technique is much more tolerant to the field variations but has much less accuracy. Since we needed to now the field map for both over target cell area and beyond we decided to simultaneously build two installations.

First equipment used for the Polarizing Magnet field mapping showed the inconsistency (see the plots) of the measurements thus forcing to design of a special equipment for high precision measurements which did include the very precise positioning (mechanical) and measuring (electronics and probes) capabilities.

Field Map of January 20, 2004



System for the precise magnet field map measurements

To drastically increase the accuracy of the measurements, the following sub-systems were designed and built.

The Positioning table.

The main requirements were:

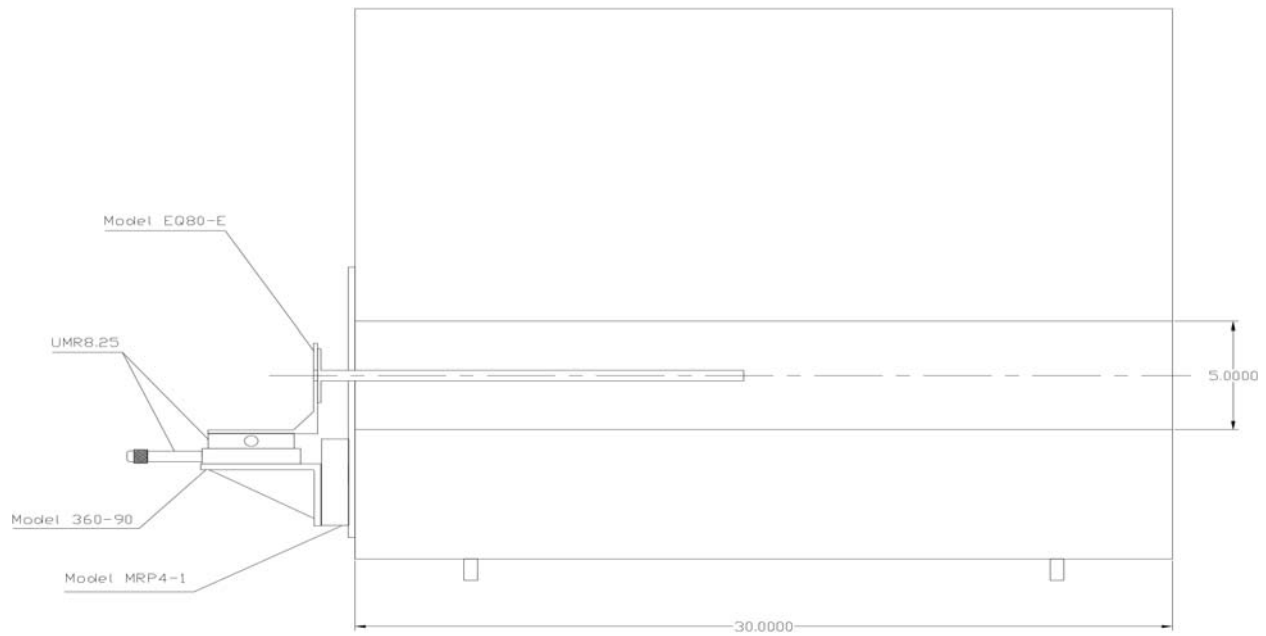
- 1) being non-magnetic not to corrupt the field of the magnet.
- 2) having fine step of thread (better then 0.1 mm).
- 3) not very expensive.
- 4) fit in the Polarizing magnet.
- 5) cover the target cell volume (D=15.0 mm; L=50.0mm)

The positioning device,

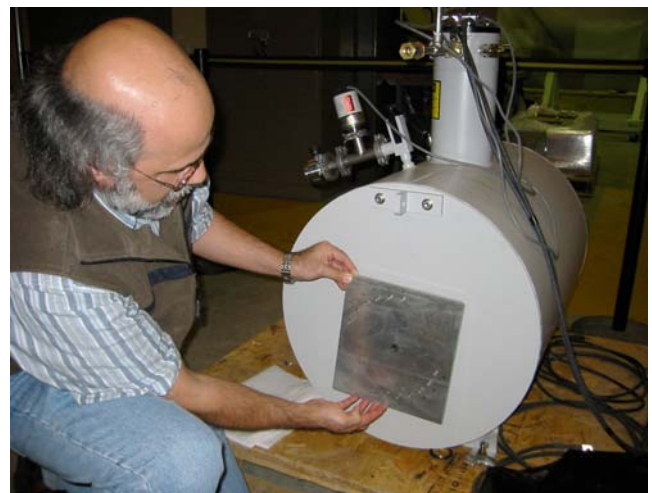
The different mechanical parts of the XY-Table were bought from Newport Corporation, (www.newport.com).



Parts (from left to right): Model EQ80-E, Model UMR8.25, Model 360-90 and Model MRP4-1



Mounting table and Polarizing Magnet assembly.



NMR-probe system



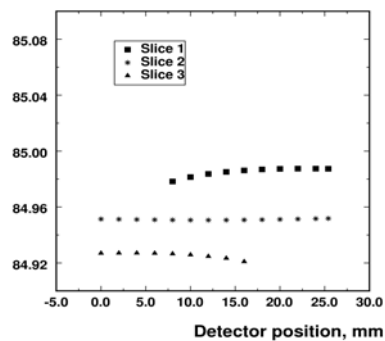
Hall-probe system



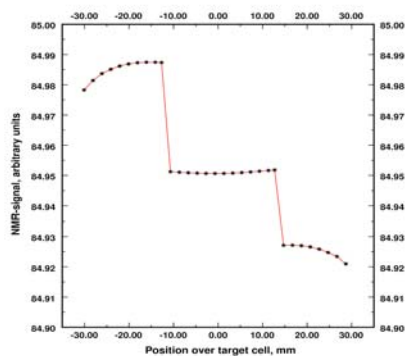
Field Map Reconstruction Procedure

Since the XY-table could only cover an area 0.5 cm in length, the whole target area, 50.0 mm, could be covered by making measurement in 0.5 steps and later by applying an “image reconstruction” procedure. To do so, we wrote special software, which reconstructed 1D and 2D field maps. The example for 1D reconstruction procedure is shown in the figures below.

NMR-signal, Arbitrary Units

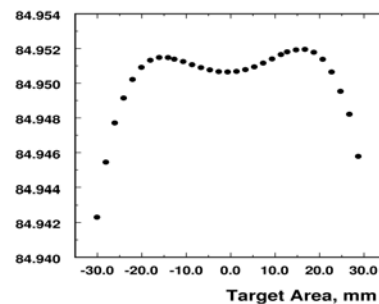


Raw Slices



NMR-signal Raw Data

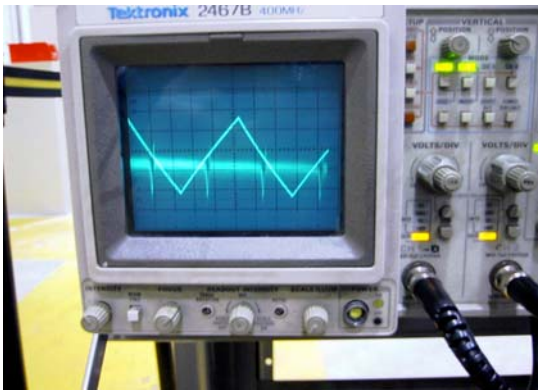
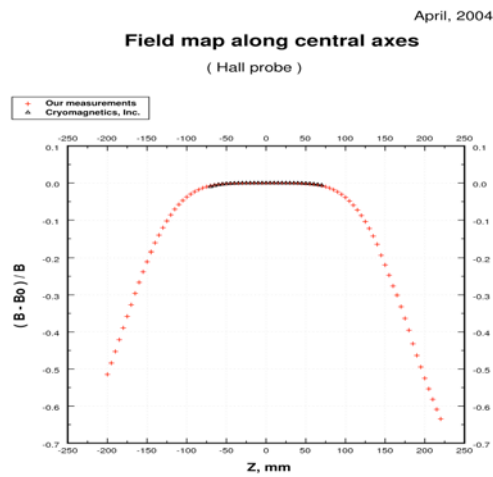
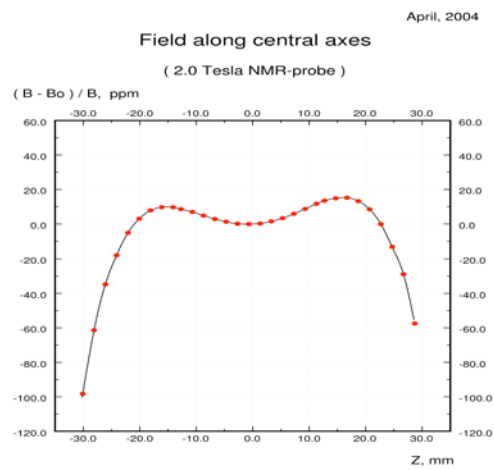
Magnetic Field, MHz (protons)



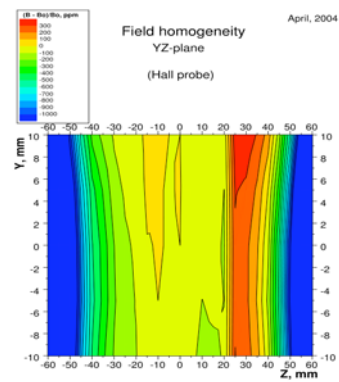
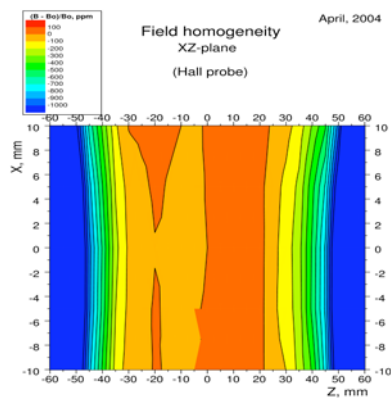
Reconstructed Field Map

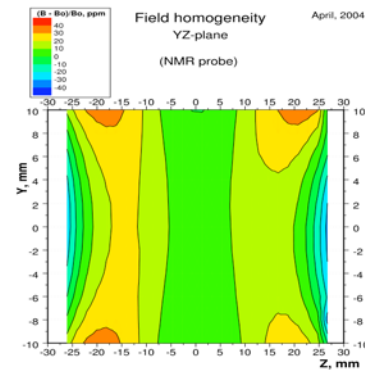
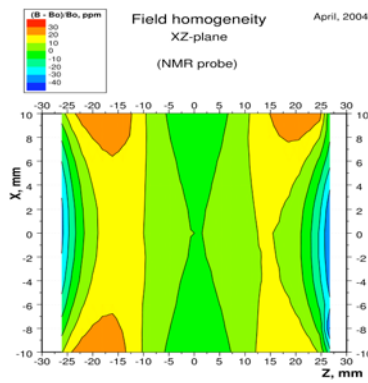
Test Results

Covered areas: NMR-probe 20x52 mm² and Hall-probe 20x120 mm²



Hall-probe 20 x 120 mm area





NMR-probe 20 x 52 mm area

Conclusions on polarizing magnet

- Hall-B polarizing magnet is very reliable.
- Homogeneity over target area, cylinder 20 x 50 mm, is better than 40 ppm (vs 100 ppm needed).
- We can use materials with paramagnetic centers, which have “narrow” (less than 100 Oe) EPR-lines.
- We can afford about 3 mm tolerance in positioning target cell (cryostat tail) over the geometrical center of polarizing magnet.

Holding magnet system

Since the polarized target for the CLAS detector will be a Frozen Spin target, a holding magnet is required for each mode of polarization (longitudinal and transverse)

Requirements

The basic requirements for the holding magnet system for the Hall-B Frozen Spin Target has been described by O. Dzyubak in Jefferson Lab Technical Notes[1]. The principle of the frozen spin target operation is to optimally polarize the target material at a high magnetic field $B = 2.5 \text{ -- } 5.0$ Tesla and low temperature around $T = 300 \text{ -- } 700$ mK and then to “freeze” the polarization at significantly lower temperatures $T = 30 \text{ -- } 70$ mK and a moderate holding magnetic field $B = 0.4 \text{--} 0.8$ Tesla. The holding field of the order of 0.5 Tesla in the target area could be produced either by the fringe field of the external Polarizing Magnet or a "small" internal magnet placed around the target.

The external Polarizing Magnets are large and have a strong fringe field. Therefore such frozen spin targets cannot be operated in combination with 4π – detectors. Using a small superconducting internal "holding magnet" allows a substantial reduction of the magnetic field affecting the detector components and particle tracking.

According to W. De Boer and T.O. Niinikoski [2], the proton spin-lattice relaxation time strongly depends on the target temperature and holding magnetic field. Below are experimentally measured values.

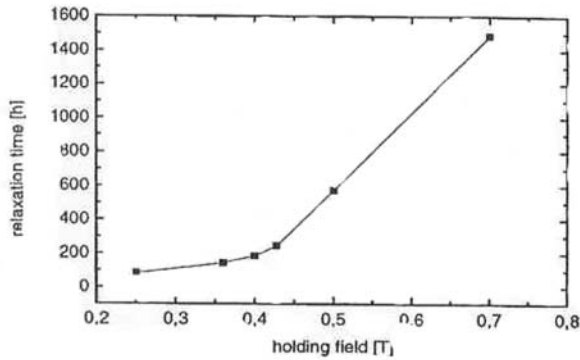


Fig. 11. Relaxation time of butanol at 60 mK.

The previous plot shows that the relaxation time is a strong function of temperature and the field “critical point” $T = 100$ mK and $B = 0.5$ Tesla. The relaxation time is changing rapidly depending on the cooling power of the dilution refrigerator, for a chosen relaxation time, we have to keep a proper combination of temperature and holding magnetic field which means for photon experiments we can afford to work at lower temperatures $T = 50$ mK (cooling power problem) and decreased holding field down to $B = 0.3$ Tesla. In contrast, for electron experiments we have to work at higher temperatures $T = 200$ mK which forces us to use holding fields up to $B = 1.0$ Tesla.

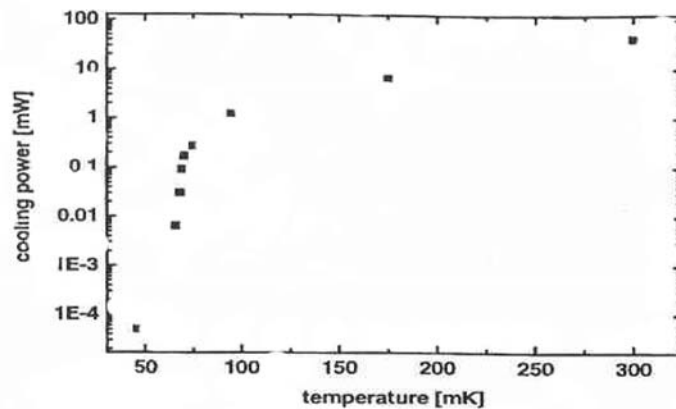


Fig. 3. Cooling power of the refrigerator.

Typical cooling power versus temperature [3].

After 100 mK, the cooling power drops pretty fast. In the frozen spin mode the refrigerator is usually operated at 50-60 mK with a cooling power of a few micro-watts.

Some Results on holding fields from other polarized target groups:

Bonn 1998 experimental setup[4]. Polarized target in combination with a full 4π -detector, experiment -- “eta-photoproduction”, material – butanol. Holding magnet system. Multi-filament NbTi wire, diam $D=100$ mkm, current $I = 7$ A (current density $J = 900$ A/mm²) at $T = 4.2$ K with the critical field $B = 1.0$ Tesla. Operating temperature $T < 1.3$ K, winding numbers $N = 5000$ (4 layers), current $I = 9.48$ A (current density $J = 1207$ A/mm²).

Polarizing field $B = 2.5$ Tesla. Max proton polarization achieved $P = 85\%$ Average proton polarization $P = 71.6\%$. Holding Mode $B = 0.38$ Tesla and $T = 57.4$ mK. The longest proton relaxation time achieved $t = 245$ hours.

GDH sum rule experiment, Mainz[4].

Polarized target in combination with a full 4- π detector. Multi-filament NbTi wire, diam $D=100$ μm , four layers of 1050 turns each. Operational temperature below 1.2 K. Max achieved current $I = 12$ A ($B = 0.48$ Tesla). Material ammonia and butanol (protons).

In the frozen spin mode with Holding field $B = 0.42$ Tesla and $T = 50\text{-}60$ mK, the relaxation time $t = 200$ hours.

Ch.Bradtko, H.Dutz, et al, Bonn,1998[5].

GDH sum rule experiment. Polarized target in combination with a full 4 π -detector. Coil temperature $T=1.2$ K, material -- butanol. The relaxation time using different frozen spin modes.

$t = 120$ hours $T = 70$ mK, $B=0.42$ Tesla

$t = 200$ hours $T = 55$ mK, $B=0.42$ Tesla

$t = 1500$ hours $T = 55$ mK, $B=0.70$ Tesla

We have contacted other Groups[6-11] and they reported the following results:

- **The Czeck target group in Prague:** material – propanediol; target dimensions -- $D=20\text{mm}$, $L=60\text{mm}$; Polarizing Mode $T = 0.3\text{-}0.8$ K, $B = 2.7$ T; Holding Mode $T=18\text{-}25\text{mK}$, $B= 0.4\text{T}$; Relaxation time $T = 250$ hours.
- **The Protvino target group in Russia:** material – pentanol; target dimensions -- $D = 20$ mm, $L = 100$ mm; Polarizing Mode $T = 0.3\text{-}0.8\text{K}$, $B = 2.08$ T; Holding Mode $T=18\text{-}25\text{mK}$, $B= 0.4\text{T}$; Relaxation time $T = 300$ hours
- **The Dubna target group in Russia:** material – propanediol; target dimensions -- $D = 20$ mm, $L = 200$ mm; Polarizing Mode $T = 0.3\text{-}0.8\text{K}$, $B = 2.7$ T; Holding Mode $T=50\text{-}60\text{mK}$, $B = 2.7$ T; Relaxation time $T = 400$ hours

Preliminary JLAB Holding Solenoid (Prototype).

Assuming that the target cell has a diameter of $D = 15$ mm and a length $L = 25$ mm, JLab made a prototype of the holding solenoid with the following parameters:

- diameter $D = 40$ mm
- length $L = 220$ mm
- thickness $\delta = 0.24$ mm
- diameter of wire $d = 0.112$ mm
- maximum current $I = 12.7$ Amps
- turns $N = 1800$ turns per layer
- layers $n = 2$ layers

With these parameters, we conducted simple calculations showing that a magnetic field in the center of such a solenoid would be 2557 Gauss (0.26 Tesla). Using the picture below, we can expect a relaxation time $t < 100$ hours in the Frozen Spin Mode with $T = 60$ mK and $B = 0.25$ Tesla.

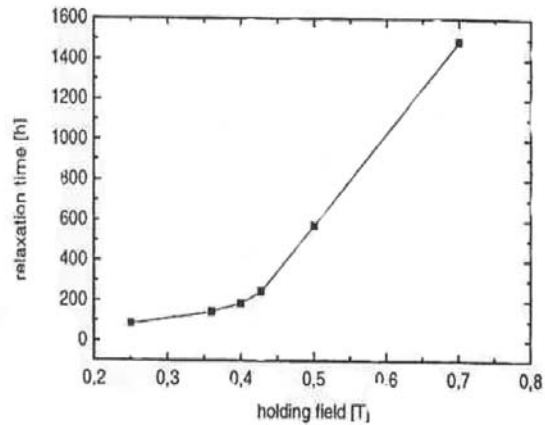
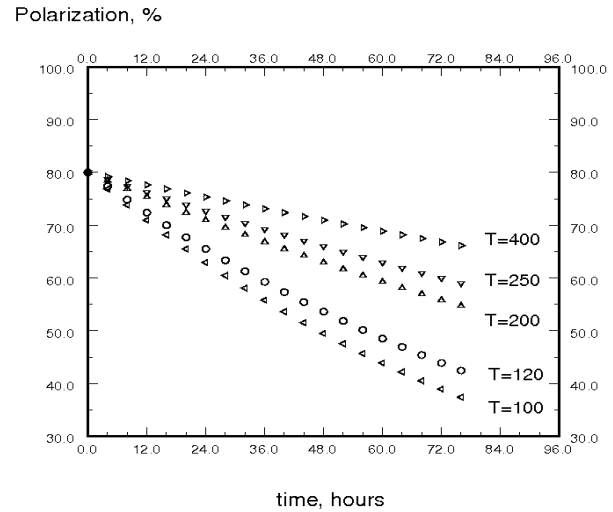


Fig. 11. Relaxation time of butanol at 60 mK.



The work cycle with different relaxation times can be estimated from the figure “Polarization drop off vs relaxation time”. Let’s assume that in the beginning of the experimental run we start with a polarization value of $P=80\%$ and that the polarization drop off should not be less than $P=75\%$. Using the previous figures, we can estimate a work cycle, the period after which we have to stop a run and polarize the target back to maximal value. Having target setup with relaxation time T_{rel} , we can expect a work cycle T_{work} as follows.

$T_{rel} = 100$ hours, $T_{work} = 4$ hours

$T_{rel} = 120$ hours, $T_{work} = 8$ hours

$T_{rel} = 200$ hours, $T_{work} = 12$ hours

$T_{rel} = 250$ hours, $T_{work} = 16$ hours

$T_{rel} = 400$ hours, $T_{work} = 28$ hours

Conclusions on the holding magnet field

- Photon experiments are supposed to work in $T = 50\text{--}60$ mK mode. For the reasonable work cycle $T_{work} = 12\text{--}16$ hours, we need a holding magnet with a field $B = 0.5$ Tesla.
- Electron experiments need more cooling power and might be run at higher temperatures $T = 100\text{--}150$ mK. In this case we need holding magnet with field $B = 0.7$ Tesla or even more.
- To satisfy both electron and photon experiments we have to consider the “universal design” of Holding Magnet with field $B = 0.7$ Tesla.

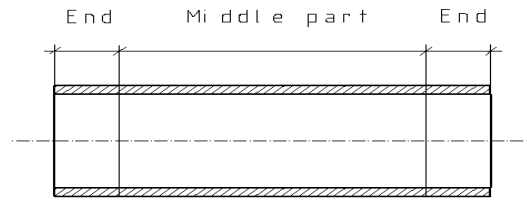
Software and Instrumentation.

Previously we reported the results of field map calculations for holding magnets which can provide the desired parameters such as a central field in the range of $0.3\text{--}0.5$ Tesla and a homogeneity better than 1% over the target cell. Those results have finalized a design of holding system in terms of shape and dimensions of magnets. After having finished the field map calculations, we started working on the mechanical parameters and, in particular, on calculating the magnetic forces acting on the conductors. Accordingly, we calculated forces for longitudinal and transverse polarization holding magnets including both 0.3 and 0.5 Tesla magnet systems.

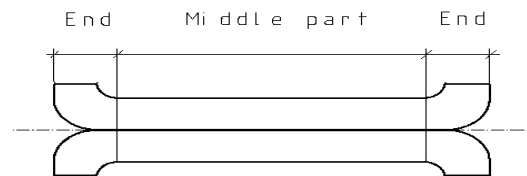
Such force calculations include two major areas of interest, the “Middles” and “Ends” of the holding magnets.

For solenoids, we used the Poisson/Superfish 2D package from Los Alamos National Laboratory. In the case of dipole force calculations, a 2D package could be use only for the “Middle” parts. For the “Ends” one had to use the Opera/Tosca commercial 3D package from Vector Fields Co.

Holding Magnets



Longitudinal Polarization
(Solenoid)

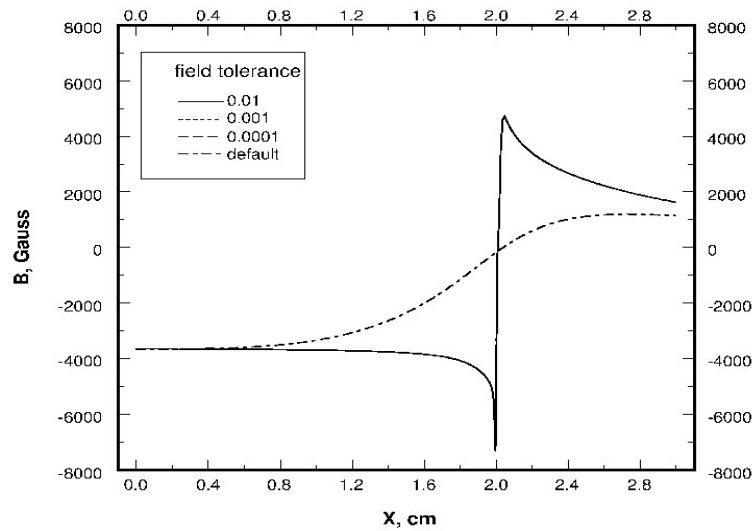


Transverse Polarization
(Dipole)

Opera(Tosca) field tolerance.

As we reported earlier, holding magnet consists of 3-4 layers with one layer thickness $h = 0.12$ mm. That defines a grid size.

By component along OX axis



While calculating a field map, we found that the Opera (Tosca) package starts “seeing” thin layers when we set up a field tolerance $\delta = 0.01$ which means that we have to use the same value of tolerance as an input

Opera (Tosca) CPU time requirements.

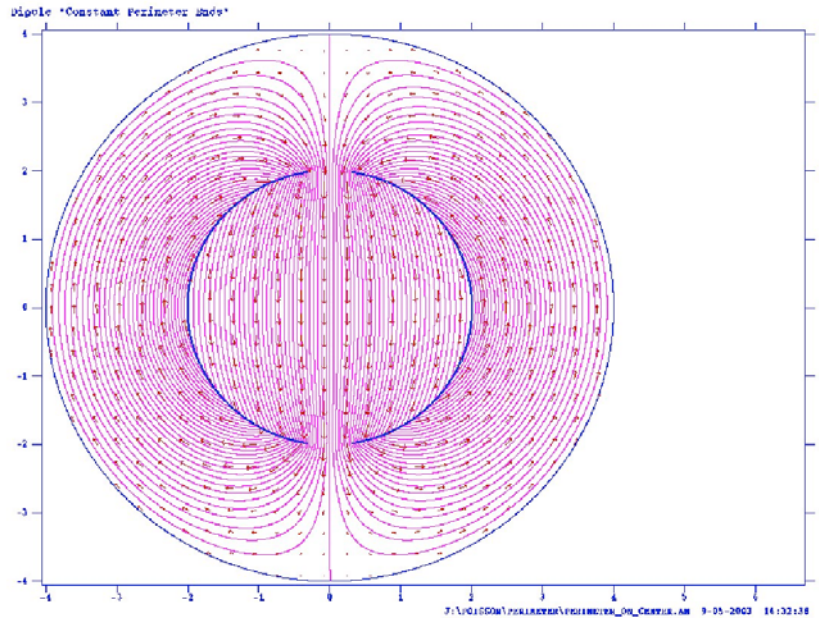
[illegible]

- 1) upgrading the CAD servers including the OPERA (Tosca) Server Application and
- 2) setting up an additional OPERA (Tosca) Server which could be used in “a single user” mode devoted to the Holding magnet system simulations.

Another way to calculate the forces was to use the Poisson/Superfish package which was an alternative to the Opera(Tosca)} approach.

- 1) Free software.
- 2) good alternative to the commercial Opera (Tosca) package.
- 3) Easy installation and setting up procedure.
- 4) very comprehensive manuals and good user support.
- 5) Outputs can be produced in a format, which can be used as an input by CAD systems, such as AutoCAD.

- 1) only 2D version.
- 2) Implemented only on Windows platforms.



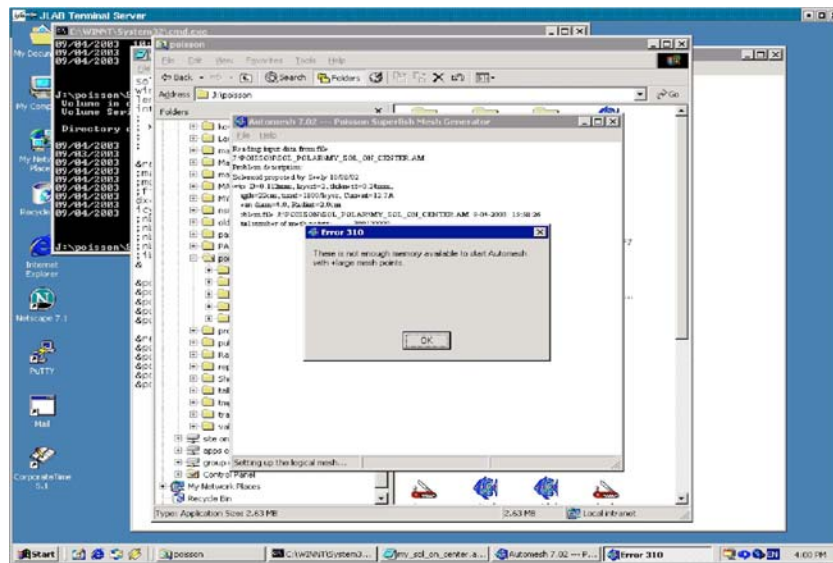
We have done the Poisson/Superfish test on the JLab Public Server. On this picture one can see a field map of our dipole but an input file has “mild” input parameters:

- 1) Dipole with only one layer, which has 1.0 mm thickness.
- 2) Mesh step size $\Delta = 1.0$ mm.

In fact, our real conditions are

- 1) magnet with four layers
- 2) mesh step size $\Delta = 0.01$ mm.

When trying to run the Poisson/Superfish with real parameters on the Windows 2000 Public Server the server crashed for “**insufficient memory to start Automesh.**”



Poisson/Superfish package requirements.

After extensive discussions with the JLab Computer Center, we came to conclusions that to be able to run the

Poisson/Superfish package we needed to build a new stand alone workstation devoted solely to our simulations which must have at least Pentium 4 2.0 GHz CPU and 2.0 GB operating memory. We ordered the necessary PC parts and built a “Standing alone” CAD workstation, installed the Poisson/Superfish package on it, and successfully finished all 2D force calculations.

Summary and conclusions on Software and Instrumentation.

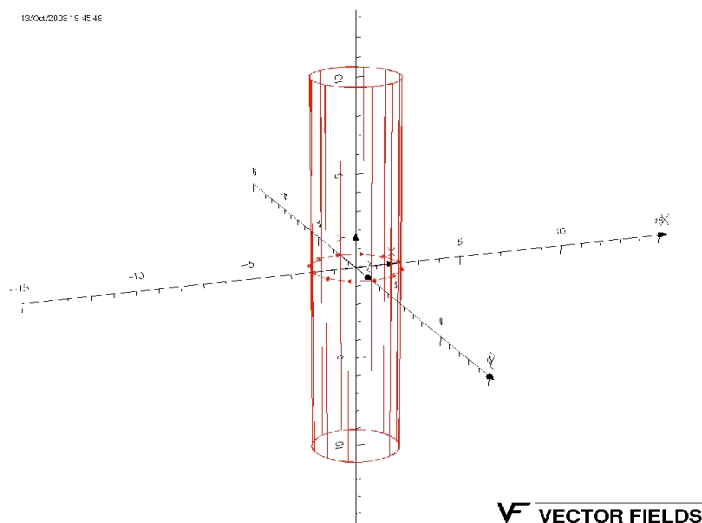
- 1) We calculated the forces for longitudinal and transverse polarizations magnet systems including both 0.3 and 0.5 Tesla holding magnets.
- 2) We calculated the forces for the both “Middles” and “Ends”.
- 3) We assembled a new dedicated CAD workstation with Poisson/Superfish installed.
- 4) We used the Poisson/Superfish package for the 2D calculations. That includes all parts for longitudinal holding magnets (solenoids) and the “Middles” of transverse holding magnets (dipoles).
- 5) After all updates were finished, we used the OPERA (Tosca) package to finish up all our 3D calculations. That included the “Ends” of dipoles.
- 6) The force calculations helped finalize the mechanical design of the holding magnet system.

Simulations and Design (Simulation Models)

The holding magnet should provide both longitudinal and transversal polarization. Such a holding system should be optimized in terms of

- 1) the room provided by a cryostat; "compact design";
- 2) a high holding field; 0.5 -- 0.7 Tesla;
- 3) providing better than 1 % homogeneity over the target cell;
- 4) being "transparent" to outgoing particles.

Longitudinal holding system Model "Solenoid"



Solenoid length -- $L = 20.0$ cm
 Current density $J = 101244.0$ A/cm²
 Number of layers $n = 2$
 Wall thickness $t = 0.24$ mm
 Mandrel diameter $D = 4.0$ cm

Such a design provides a magnetic field on the solenoid center $B = 0.3$ Tesla with homogeneity over target cell better than 1%.

Transversal holding system. Racetrack

The required holding field over the target volume can be provided if a dipole is wrapped on a mandrel with the following dimensions:

Diameter of a mandrel $D = 40$ mm

Length of a mandrel $L = 300$ mm

The first model studied was the so-called "Racetrack" magnet:

Coil length $L = 300$ mm

Layer width $A = 38$ mm

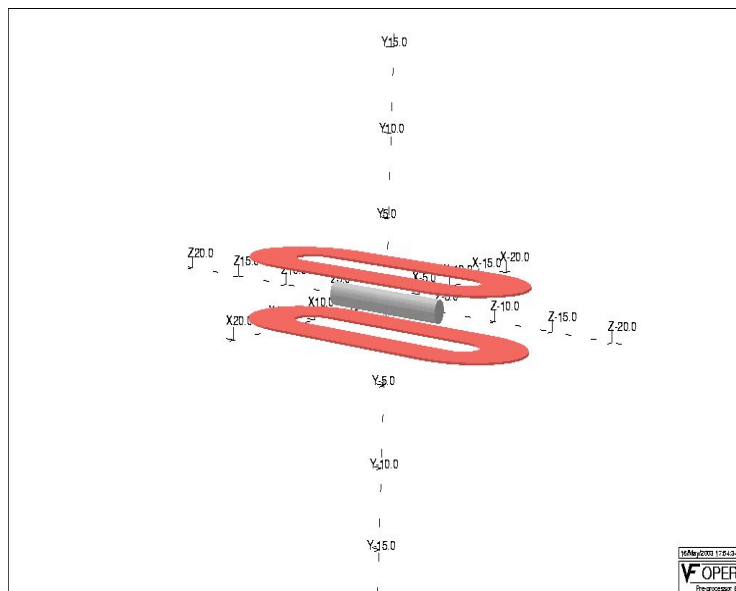
Overall layer thickness $h = 1$ mm

Distance between coils $H = 36.6$ mm

Wire diam $D = 0.112$ mm

Max current $I = 12.7$ A

Layers $N = 9$



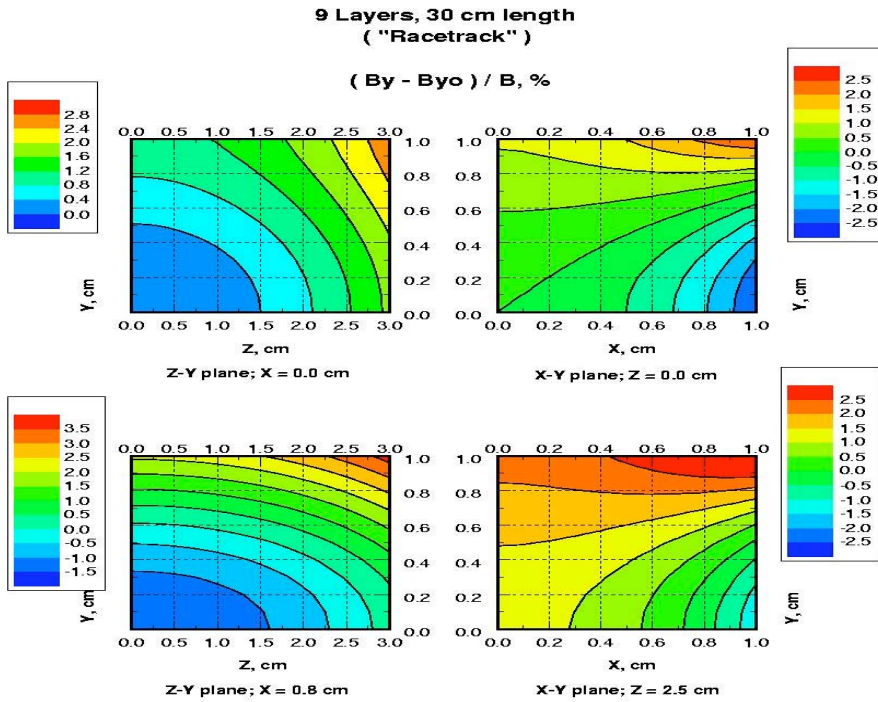
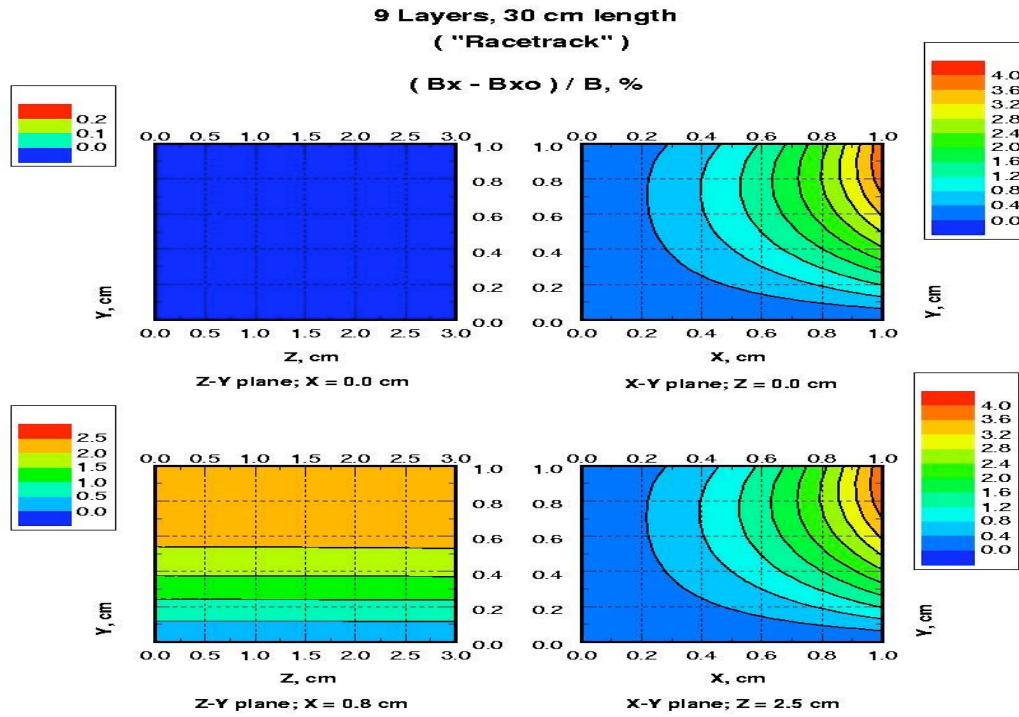
Such a dipole provides a central field $B_{\text{max}} = 0.7$ Tesla. This model was used to calculate an additional field produced by holding magnet inside the JLab CLAS detector. The calculated field map is kept on "work/clas/gsim" public domain and is used for modeling the equipment (in particular the start counter) located around the polarized target inside CLAS.

Advantages

- 1) very simple in modeling and production
- 2) provides required holding field ($B = 0.7$ Tesla)
- 3) provides 1% B_y homogeneity over target volume

Disadvantages

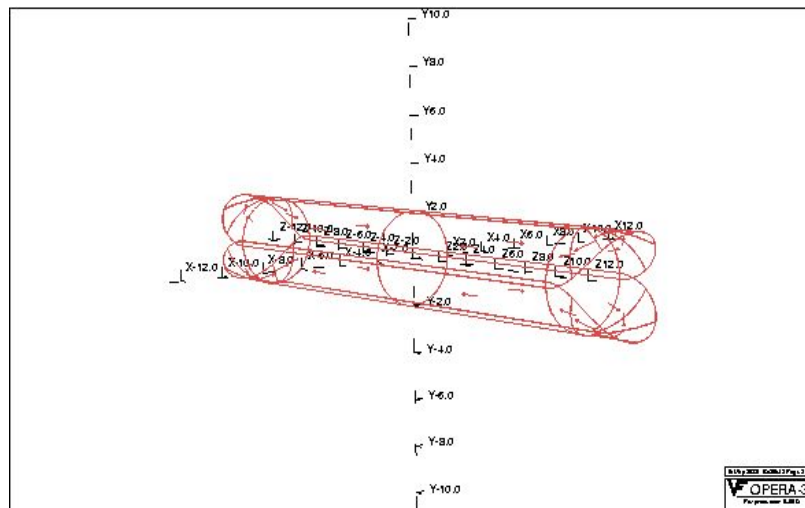
- 1) doesn't fit the shape of the heat shield of the cryostat
- 2) is not convenient for use inside the cryostat
- 3) has a highly "undesirable" B_x component, more than 3 %



Simulation for this model has been expanded over the large internal volume of the CLAS detector.

“Constant Perimeter Ends curved and fitting the cylinder”

The second model was the “Constant Perimeter Ends curved and fitting the cylinder” model as a basic model with the following parameters.



Mandrel length $L = 300, 250, 240, 200$ mm

Mandrel diameter $D = 40$ mm

Overall layer thickness $h = 0.5$ mm

Wire diameter $d = 0.14$ mm

Current $I_{\text{max}} = 25$ A

Amount of layers $N = 3$ and $N = 4$

Advantages

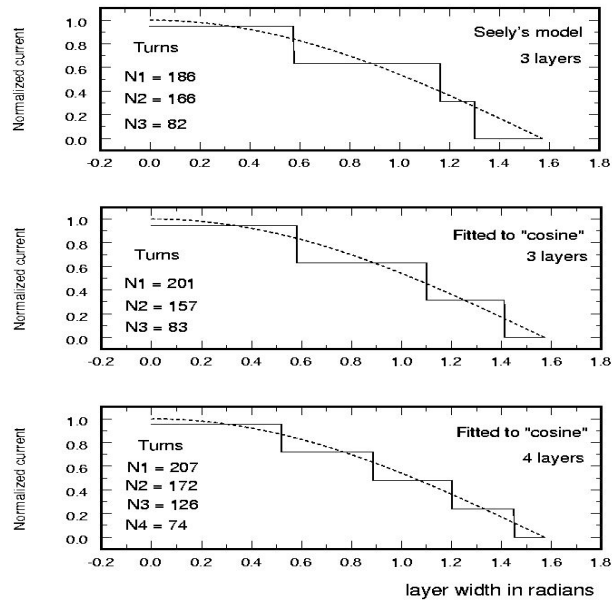
- 1) fits a shape of a heat shield of the cryostat
- 2) very convenient to use inside the cryostat
- 3) provides high homogeneity over target volume

Disadvantages

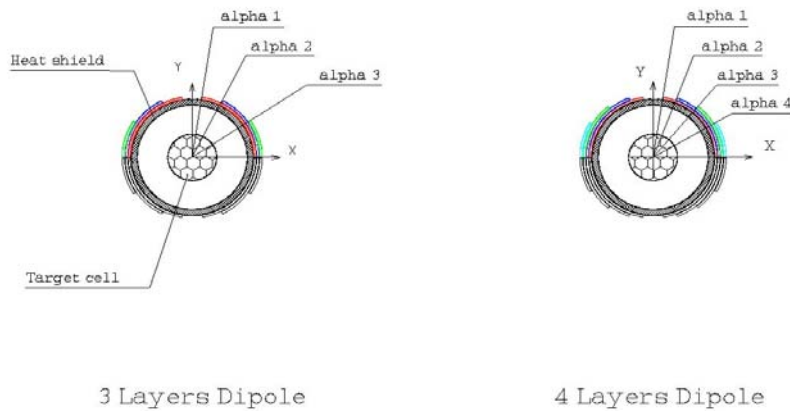
- 1) complicated in both manufacturing and modeling

For a better field performance we used dipoles with layers fitted to the “cosine” shape of conductor distribution. We wrote a special program, which optimized a configuration for both three and four layers geometry.

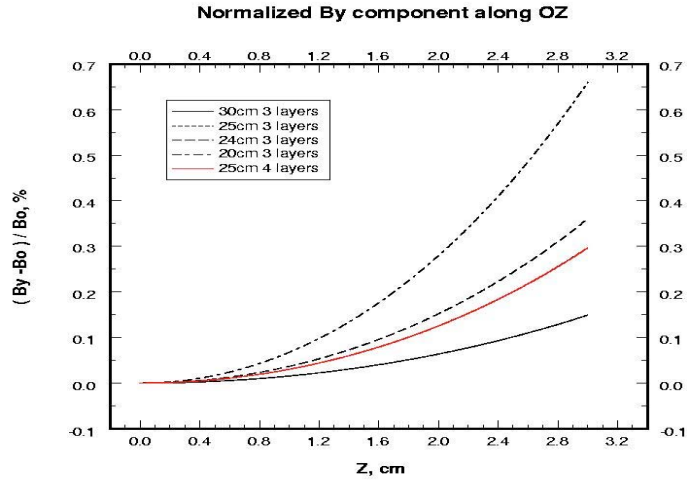
Dipoles with "cosine" conductor distribution



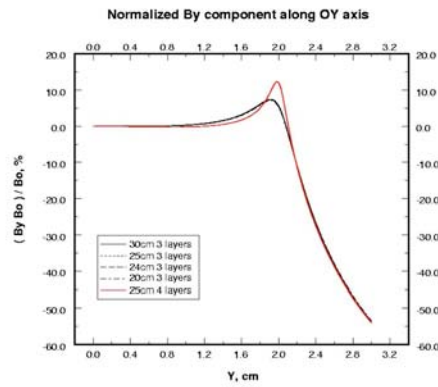
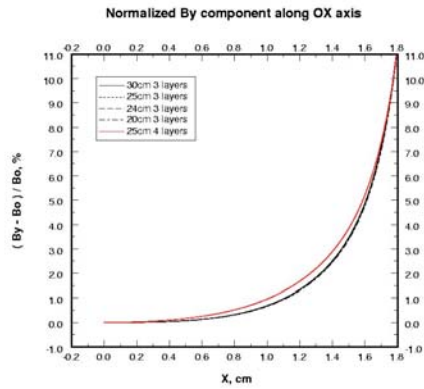
Optimization gives us dipoles wrapped on 40 mm in diameter heat shield with a variable width of layers (see fig).



In terms of the "compact design" model, we've studied a field homogeneity vs dipole length. As can be seen, it's possible to decrease the length for both 3 and 4 layer dipoles down to $L = 25$ cm and still keep the B_y homogeneity in longitudinal direction less than 0.4% over target length 5.0 cm.



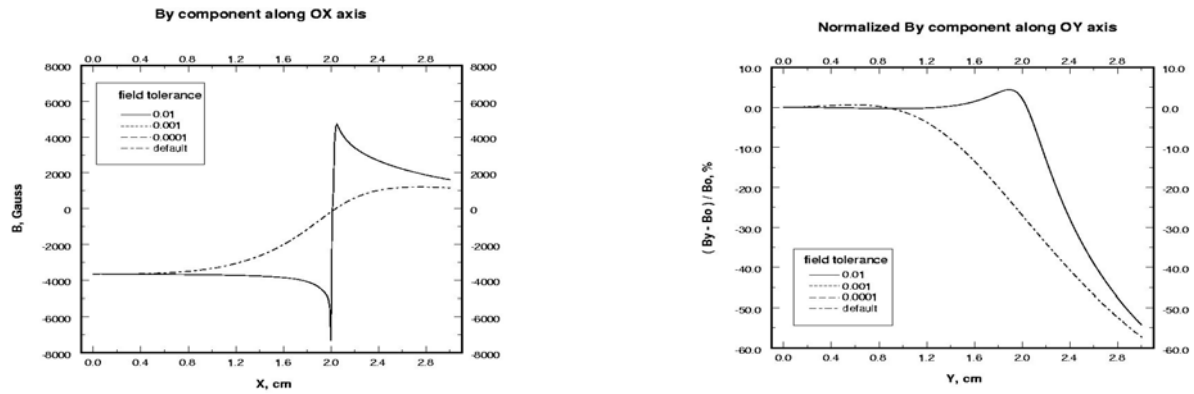
Decreasing the dipole length does not change B_y homogeneity in both OX and OY transversal directions and it is still less than 0.5% over target diameter $D = 1.5$ cm.



Far from the conductor, the normalized B_y component along the direction of a target polarization converges to the same value for all studied dipoles.

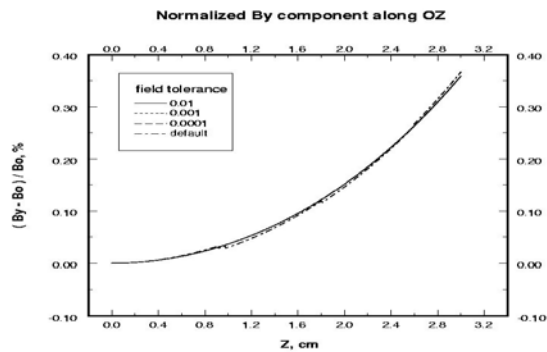
In terms of protection against quenching, we have calculated peak field on the conductors. Default Tosca

(OPERA) package configuration is pretty fast and gives an accurate field evaluation "far away" from the conductors. To estimate the peak field on the conductors, we changed the configuration to a better field tolerance. A better field tolerance consumes much more CPU time. In fact, as can be seen from the plots, a field



tolerance 0.01 is quite enough. So we changed defaults to keep the configuration with 0.01 field tolerance.

B_y component on the central axis along OZ direction is not very sensitive to changing field tolerance.



So for field map calculations "far away" from conductors, the use of "native" defaults of Tosca (OPERA) package configuration saves CPU time and still gives reliable results.

For the mono-filament superconducting wire which we used for modeling, critical currents at 4.2 K are

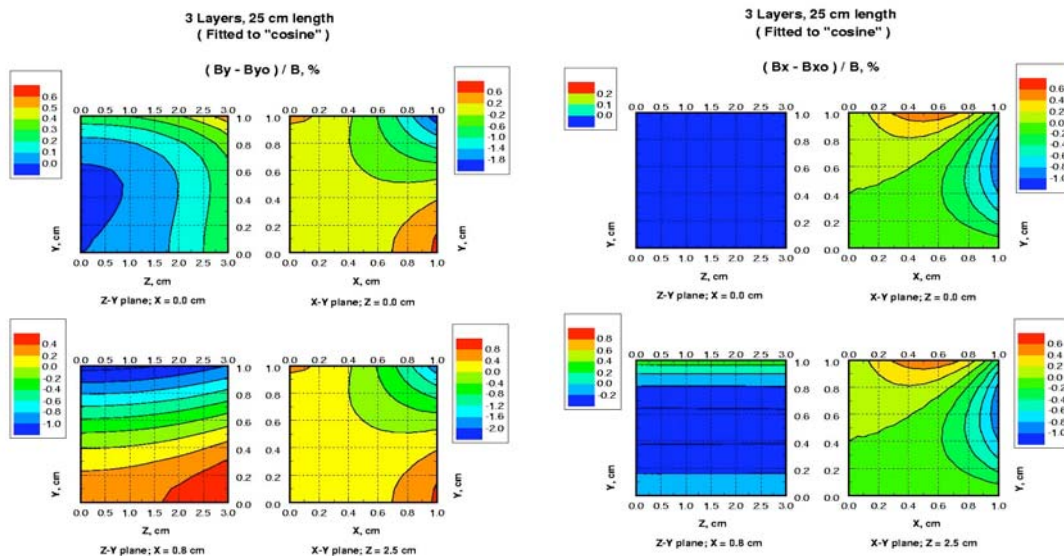
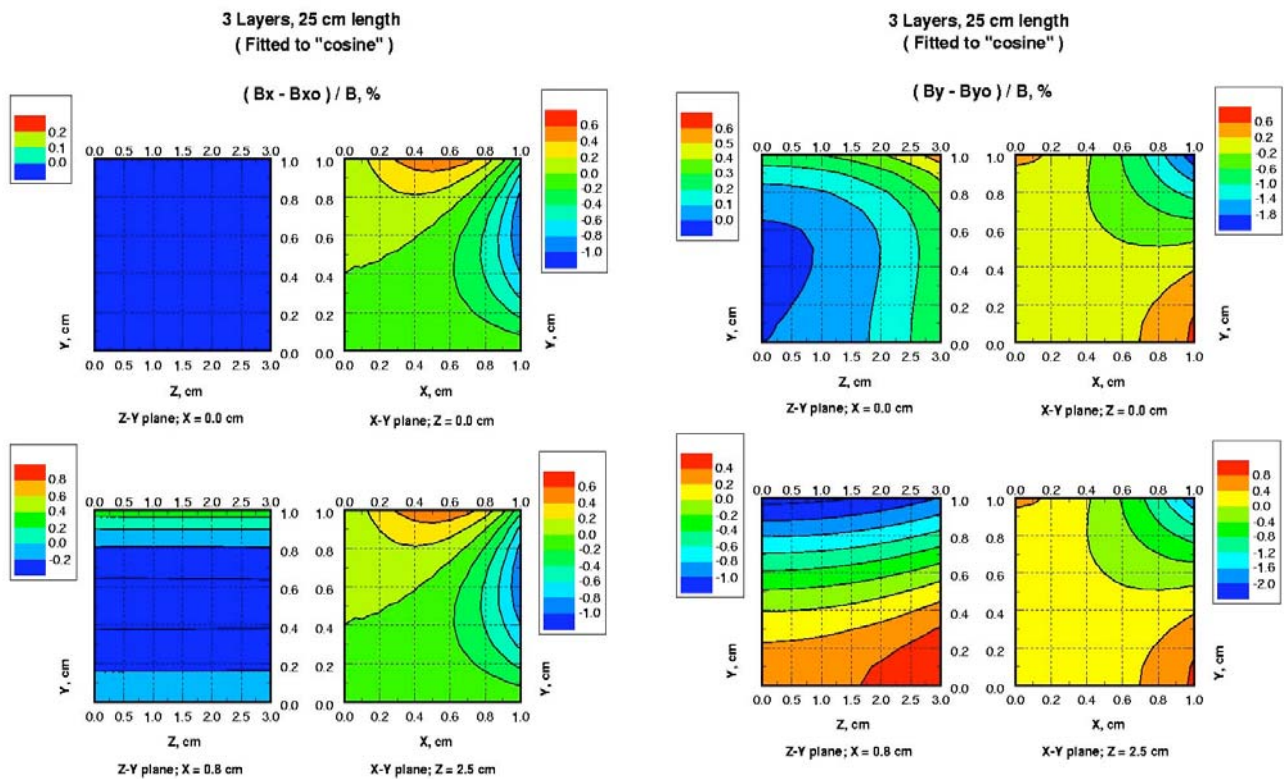
$I_{cr} = 130$ Amps at $B = 3$ Tesla

$I_{cr} = 90$ Amps at $B = 5$ Tesla

$I_{cr} = 60$ Amps at $B = 7$ Tesla

$I_{cr} = 20$ Amps at $B = 9$ Tesla

In our case we do not exceed the critical parameters for all studied dipoles that means we still can use the same kind of a mono-filament superconducting wire for manufacturing dipoles. 3 layers, 25 cm dipole field homogeneity (model fitted to "cosine" shape by program)



Fitted dipole provides

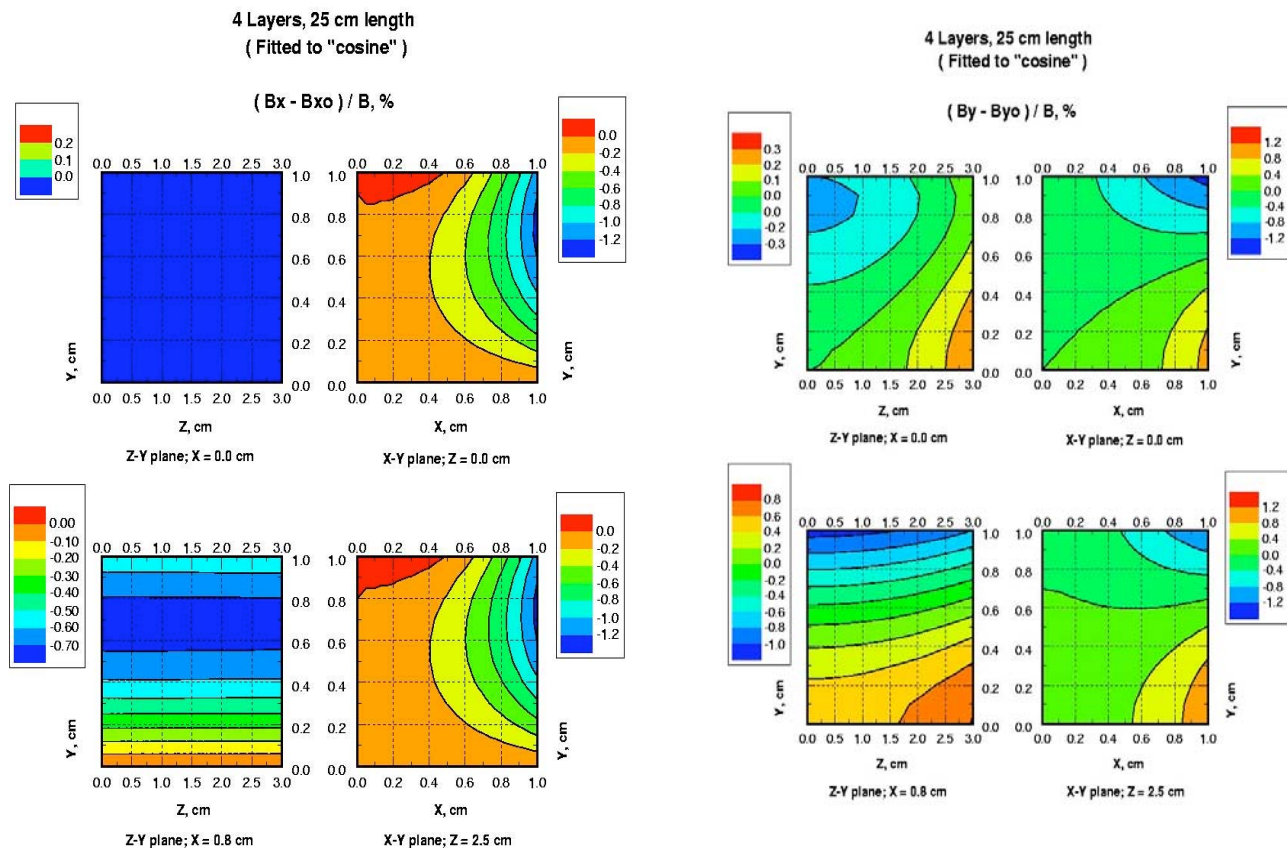
Central field B = 0.36 Tesla

Field homogeneity over target volume 0.8 in longitudinal 0.8% in transversal direction

Additional B_x component 0.2% in longitudinal 0.4% in

transversal direction

4 layers, 25 cm dipole field homogeneity (Model fitted to ``cosine" shape by program)



Fitted dipole provides

Central field B = 0.48 Tesla

Field homogeneity over target volume

0.6% in longitudinal

0.8% in transversal direction

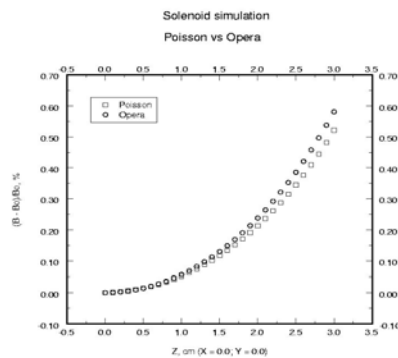
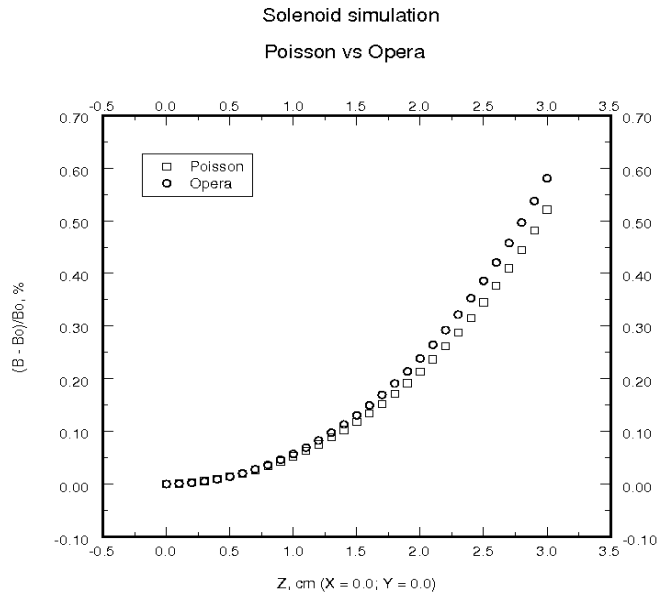
Additional B_x component

0.6% in longitudinal

0.6% in transversal direction

In terms of the mechanical design, we have also calculated the forces acting on the conductors. Such force calculations include the two major areas of interest, the "Middles" and "Ends" of the holding magnets.

For the solenoids, we used the Poisson/Superfish 2D package. For the dipole force calculations, the 2D package could be used only for the "Middle" parts. For the "Ends" one had to use the Tosca (Opera) commercial 3D package.



Longitudinal holding system (solenoid).

The two layers solenoid is considered as one thick layer (0.24 mm) solenoid.

To calculate the force distribution, we consequently considered an entire solenoid as a solenoid consisting of one, three, four, and eight pieces. Such a method gives us an idea about a force distribution on the both center and ends of the holding solenoid.

1) One piece solenoid

- a) no tangential component
- b) radial component $F_r = 6.22$ N/radian per 1 cm of solenoid length

2) Three pieces solenoid

Central part

- a) no tangential component
- b) radial component $F_r = 6.7$ N/radian per 1 cm of solenoid length

Ends

- a) tangential $F_z = 1.38$ N/radian per 1 cm of solenoid length
- b) radial component $F_r = 5.74$ N/radian per 1 cm of solenoid length

Net force $F = 5.9$ N/radian per 1 cm of solenoid length; $\alpha = 13$ degrees (angle counted from the line perpendicular to the central axis of solenoid)

3) Four pieces solenoid

Central parts

- a) no tangential component
- b) radial component $F_r = 6.7$ N/radian per 1 cm of solenoid length

Ends

- a) tangential $F_z = 1.38$ N/radian per 1 cm of solenoid length
- b) radial $F_r = 5.74$ N/radian per 1 cm of solenoid length

Net force $F = 5.9$ N/radian per 1 cm of solenoid length; $\alpha = 13$ degrees

4) eight pieces solenoid

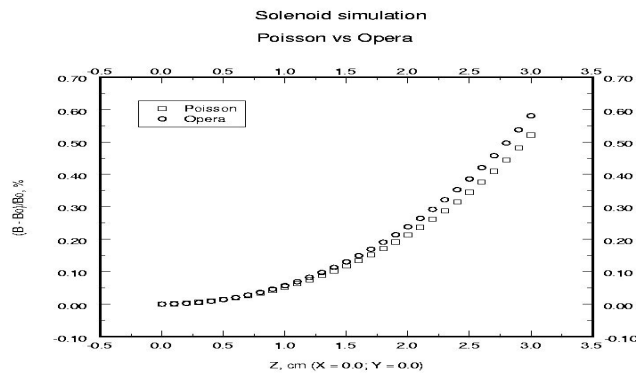
Central parts

- a) no tangential component
- b) radial $F_r = 6.7$ N/radian per 1 cm of solenoid length

Very End

- a) tangential $F_z = 2.4$ N/radian per 1 cm of solenoid length
- b) radial $F_r = 5.1$ N/radian per 1 cm of solenoid length

Net force $F = 5.6$ N/radian per 1 cm of solenoid length; $\alpha = 25$ degrees



Longitudinal holding system (solenoid).

Two layers solenoid is considered as one thick layer (0.24 mm) solenoid.

To calculate the force distribution, we consequently considered an entire solenoid as a solenoid consisting of one, three, four, and eight pieces. Such a method gives us an idea about the force distribution on the both center and ends of the holding solenoid.

1) One piece solenoid

- a) no tangential component
- b) radial component $F_r = 6.22$ N/radian per 1 cm of solenoid length

2) Three pieces solenoid

Central part

- a) no tangential component
- b) radial component $F_r = 6.7$ N/radian per 1 cm of solenoid length

Ends

- a) tangential $F_z = 1.38$ N/radian per 1 cm of solenoid length
- b) radial component $F_r = 5.74$ N/radian per 1 cm of solenoid length

Net force $F = 5.9$ N/radian per 1 cm of solenoid length; $\alpha = 13$ degrees

3) Four pieces solenoid

Central parts

- a) no tangential component
- b) radial component $F_r = 6.7$ N/radian per 1 cm of solenoid length

Ends

- a) tangential $F_z = 1.38$ N/radian per 1 cm of solenoid length
- b) radial $F_r = 5.74$ N/radian per 1 cm of solenoid length

Net force $F = 5.9$ N/radian per 1 cm of solenoid length; $\alpha = 13$ degrees

4) eight pieces solenoid

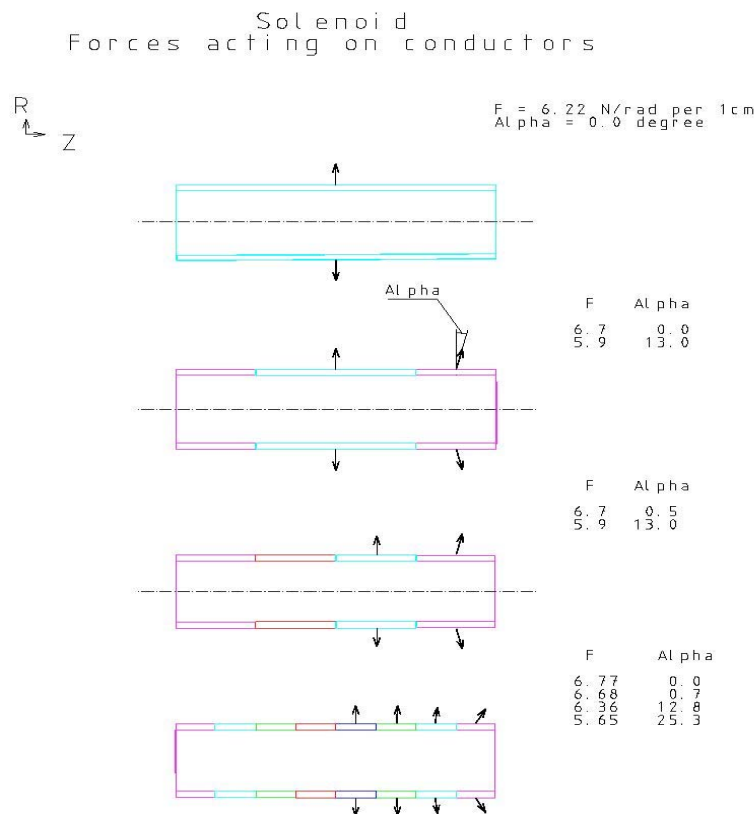
Central parts

- a) no tangential component
- b) radial $F_r = 6.7$ N/radian per 1 cm of solenoid length

Very End

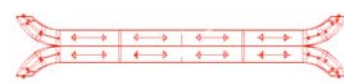
- a) tangential $F_z = 2.4$ N/radian per 1 cm of solenoid length
- b) radial $F_r = 5.1$ N/radian per 1 cm of solenoid length

Net force $F = 5.6$ N/radian per 1 cm of solenoid length; $\alpha = 25$ degrees



Transversal holding system (dipole).

Results of calculations of forces acting on conductors of the holding magnet system for transversal polarization.



$I_{max} = 25$ Amps; Current density $J = 127551.0$ Amps/cm²

3 conductors

Conductor 1:

Cross section: 0.014 2.821

Angle of straight and cutter: 40.4 90.0

Length: 9.4

Radius of mandrel and cutter: 2.0 2.0

Current Density: 127551.0, Drive label: 'ONE'

Total current: 5037.499194

Flux density tolerance: 0.01

Conductor 2:

Cross section: 0.014 2.2

Angle of straight and cutter: 31.49 90.0

Length: 9.4

Radius of mandrel and cutter: 2.014 2.014

Current Density: 127551.0, Drive label: 'TWO'

Total current: 3928.5708

Flux density tolerance: 0.01

Conductor 3:

Cross section: 0.014 1.164

Angle of straight and cutter: 16.66 90.0

Length: 9.4

Radius of mandrel and cutter: 2.028 2.028

Current Density: 127551.0, Drive label: 'THREE'

Total current: 2078.571096

Flux density tolerance: 0.01

Layer 1 (201 turns)

At (1.5 ;1.3 4.7) force = (168.66; -12.1; 0.0) $F_t = 169.1$ N (18.0 N/ cm); Alpha = -4.1 Grad

At (1.5; 1.3 9.8) force = (16.6; 0.70; 1.8) $F_t = 16.7$ N

At (1.2; 1.6; 10.6) force = (10.3; 2.0; 5.2) $F_t = 11.7$ N

At (0.5; 2.0; 11.1) force = (1.8; -2.12 ; 8.3) $F_t = 8.8$ N

Layer 2 (157 turns)

At (1.72; 1.06; 4.7) force = (43.7; -51.7; 0.0) $F_t = 67.7$ N (7.2 N/cm) Alpha = -49.77 Grad

At (1.67; 1.11; 9.9) force = (8.1 ; -2.6; 1.7) $F_t = 8.8$ N

At (1.34; 1.51; 10.9) force = (2.3; -4.3; 4.7) $F_t = 6.8$ N

At (0.54; 1.96; 11.4) force = (-0.6; -6.6; 5.6) $F_t = 8.7$ N

Layer 3 (83 turns)

At (1.95; 0.58; 2.35)	force = (-17.0; -17.75; 0.0)	F _t = 24.6 N (5.2 N/cm)	Alpha = 226.2 Grad
At (1.95; 0.58; 7.05)	force = (-16.11; -18.0; 0.0)	F _t = 24.2 N (5.1 N/cm)	Alpha = 228.2 Grad
At (1.92; 0.67; 10.07)	force = (-4.78; -3.9; 0.55)	F _t = 6.2 N	
At (1.60; 1.25; 11.24)	force = (-4.54; -4.9; 1.17)	F _t = 6.8 N	
At (0.67; 1.93; 11.90)	force = (-2.0; -6.8; 1.5)	F _t = 7.2 N	

Conclusions on simulations of Holding system

We have found an optimal design of dipoles for the transversal holding system:

- 1) 3 layers dipole provides central field $B = 0.36$ Tesla.
- 2) 4 layers dipole provides central field $B = 0.48$ Tesla.
- 3) Both 3 and 4 layers dipoles fitted to “cosine” shape can provide a field homogeneity over the whole target cell better than 1%.
- 4) Keeping 1% homogeneity, the dipole length can be reduced down to $L = 20$ cm.
- 5) The peak field on the conductors is still far from critical parameters.
- 6) Our calculations of forces acting on the conductors has helped finalize the design of the holding magnet system for transverse polarization.

Experimental Test of Holding System Prototypes

The experimental tests have been done by USC post doc O. Dzyubak and USC graduate student N. Recalde. Results have been reported at the APS annual meeting and have been included in the Master Thesis of N. Recalde.

Conditions of field map measurements:

- 1) Both mapping and simulations have been done for the target cell prototype with $D=1.5$ cm and $L=2.5$ cm
- 2) Normal Conditions $I = 30$ mA @ $T = 300$ K (not superconducting mode)
- 3) Type of probe: Solid state Hall effect generator
- 4) Simulation tool: Tosca program for SOLENOID and BEDSTEAD
- 5) Comparison of results Formulas, Experimental results and Tosca
- 6) Any direction considered according to beam line

Prototype of Holding system for transversal polarization

BEDSTEAD Parameters.

Length -- 24.89 cm

Diameter -- 8.28 cm

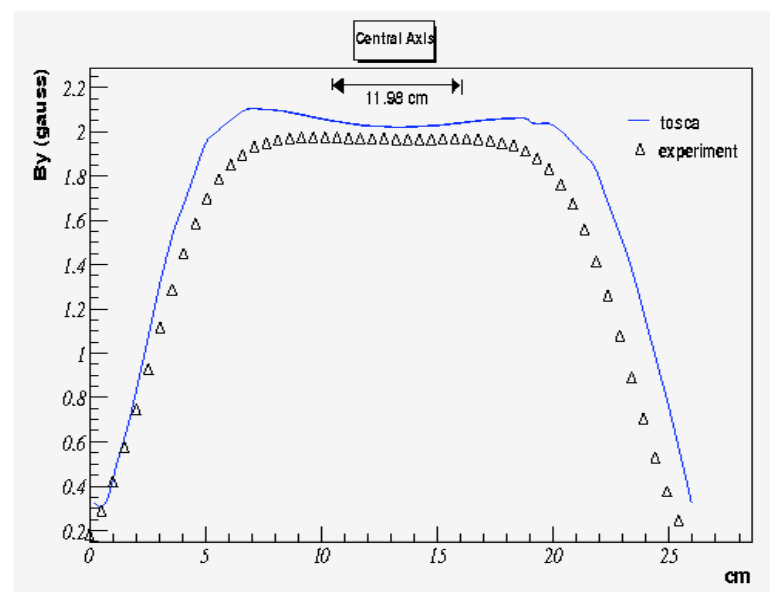
Layers -- 1 layer

$I = 35.6$ mA

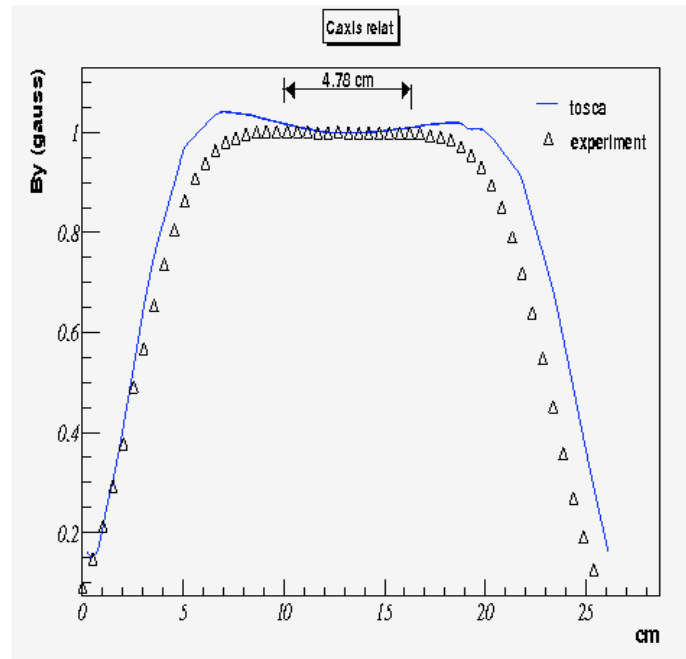
$J = 356.00$ A/cm²

$N = 340$ turns

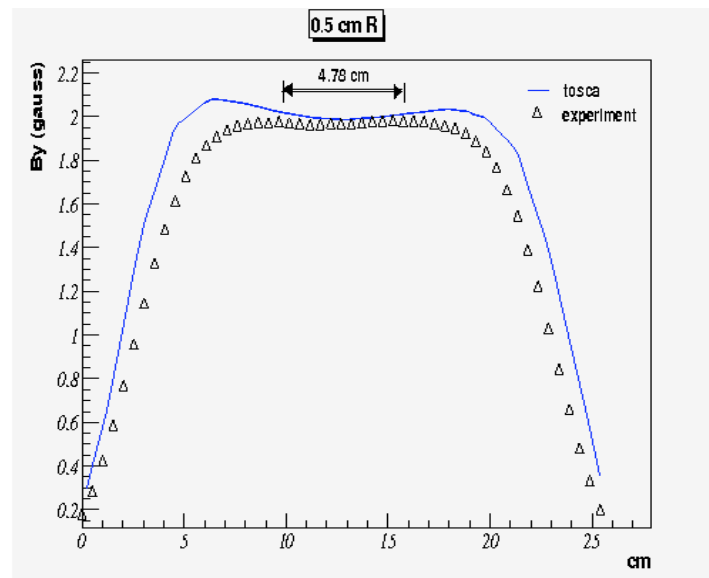
wire $D = 0.10$ mm



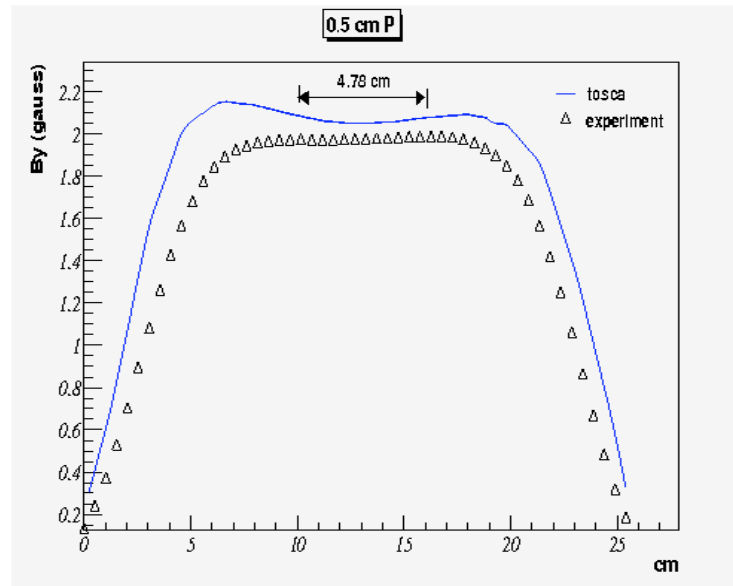
- 1) The values were taken on the central axis inside bedstead
- 2) "0" represents the beginning of winding
- 3) The length 11.98 cm represents a field homogeneity of 1%



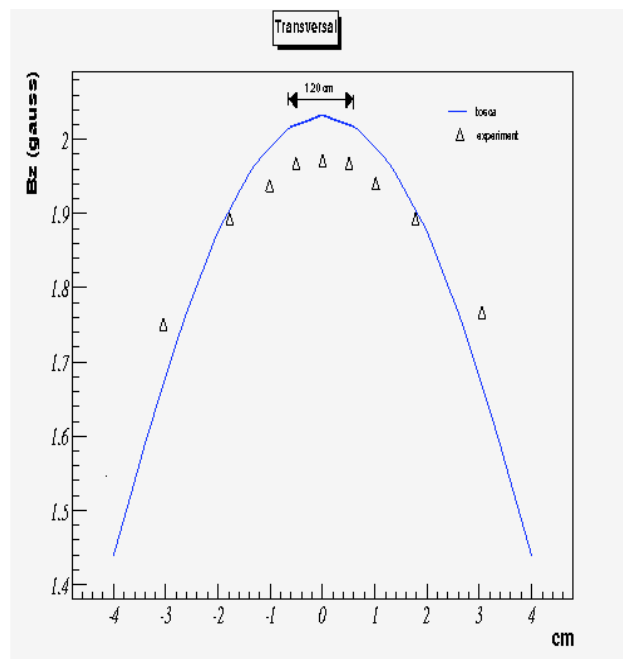
- 1) The values were taken on the central axis inside bedstead
- 2) "0" represents the beginning of winding
- 3) Magnetic field normalized by field on the center (B_i/B_o)



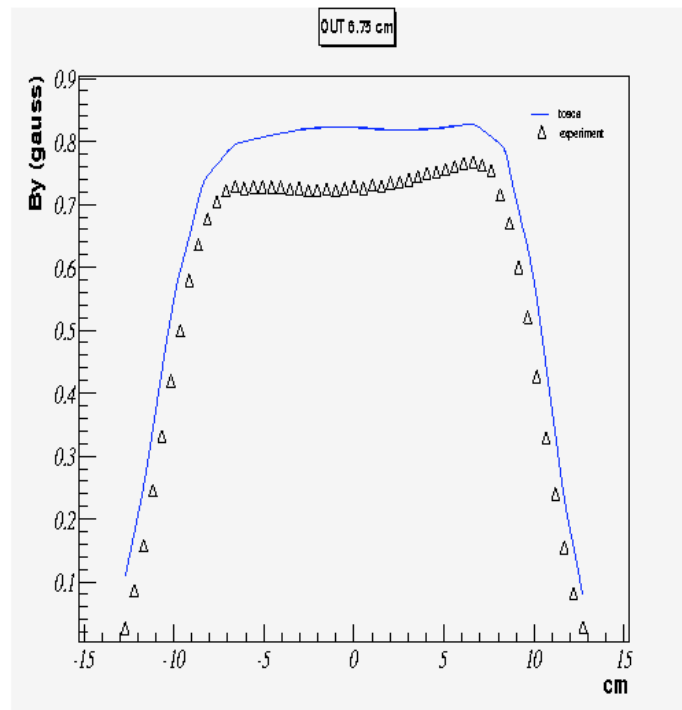
- 1) The values were taken in longitudinal direction with a 0.5 cm shift in transversal direction to the beam line and longitudinal direction to the magnetic field
- 2) "0" represents the beginning of winding
- 3) The length 4.78 cm represents a field homogeneity of 1 %



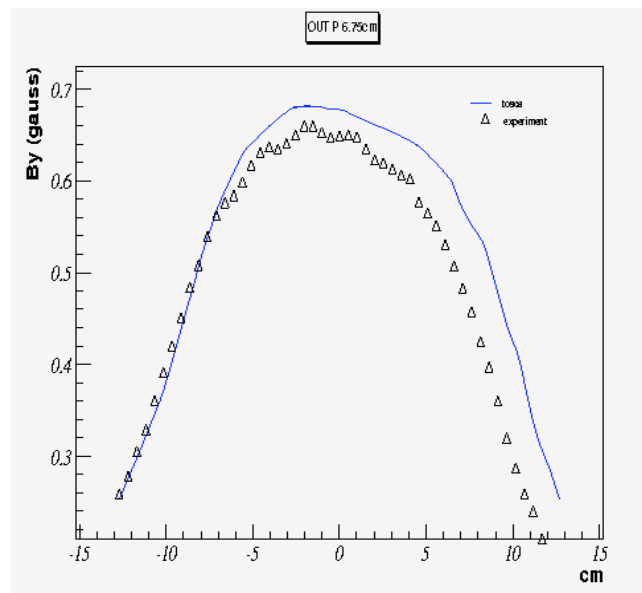
- 1) The values were taken in longitudinal direction with a 0.5 cm shift in transversal direction to the both beam line and magnetic field
- 2) "0" represents the beginning of winding
- 3) The length 4.78 cm represents a field homogeneity of 1 %



- 1) The values were taken in transversal direction to the beam line and longitudinal direction to the magnetic field
- 2) "0" point represents bedstead geometrical center
- 3) The length 1.20 cm represents a field homogeneity of 1 %



- 1) Transversal magnetic field outside the bedstead
- 2) "0" represents bedstead geometrical center
- 3) The values were taken in longitudinal direction with a 6.75 cm shift in transversal direction to the beam



line and longitudinal direction to the magnetic field

- 1) Transversal magnetic field outside the bedstead
- 2) "0" represents bedstead geometrical center
- 3) The values were taken in longitudinal direction with a 6.75 cm shift in transversal direction to the both beam line magnetic field

Prototype of the holding magnet for longitudinal polarization

SOLENOID parameters.

Length -- 15.24 cm

Diameter -- 4.0 cm

$I = 24.36 \text{ mA}$

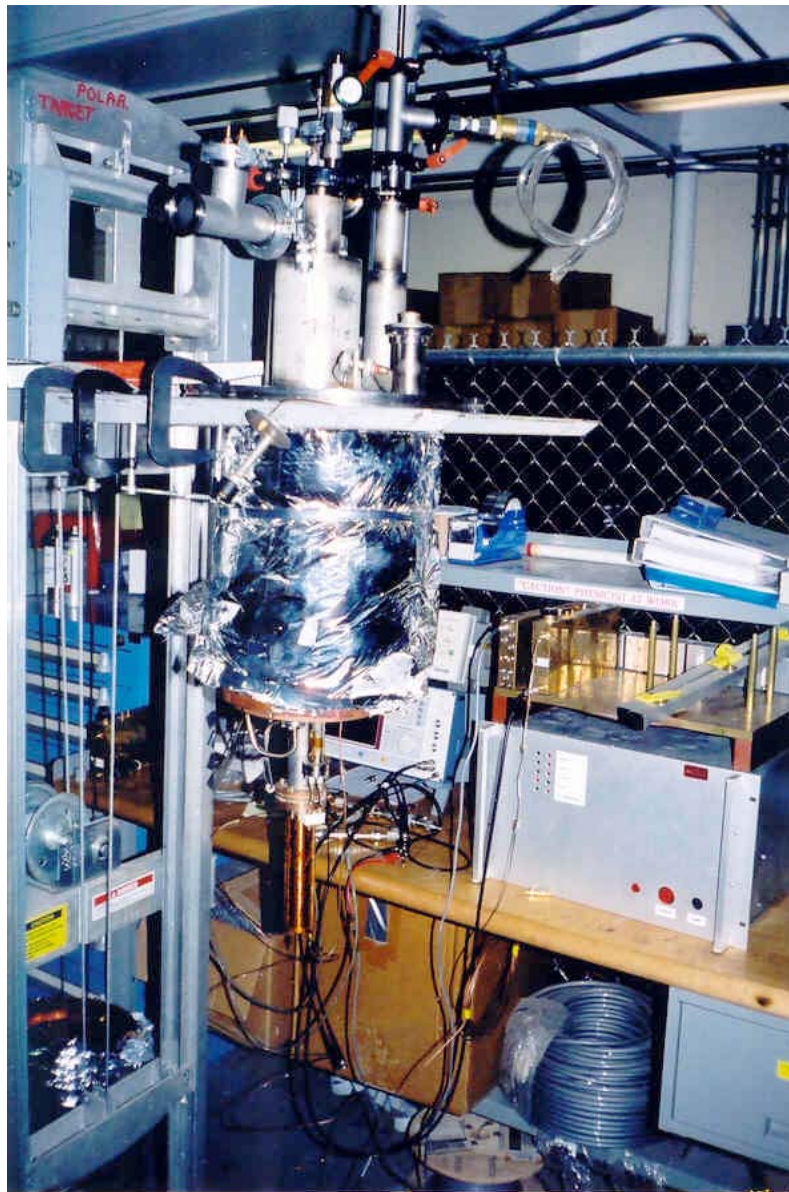
$J = 239.8 \text{ A/cm}^2$

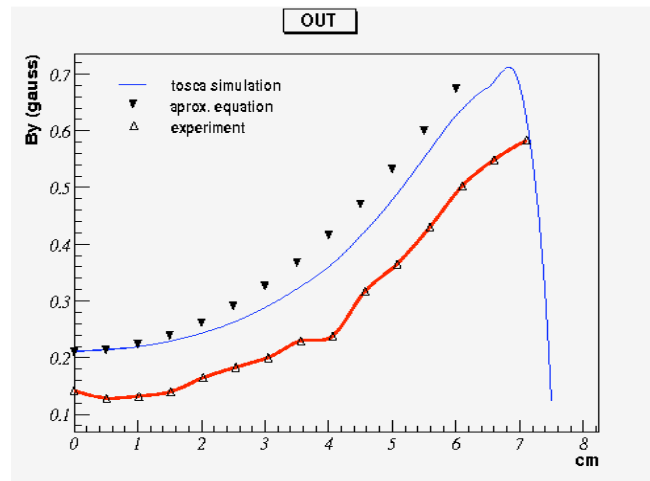
$N = 3600 \text{ turns}$

$L = 2 \text{ layers}$

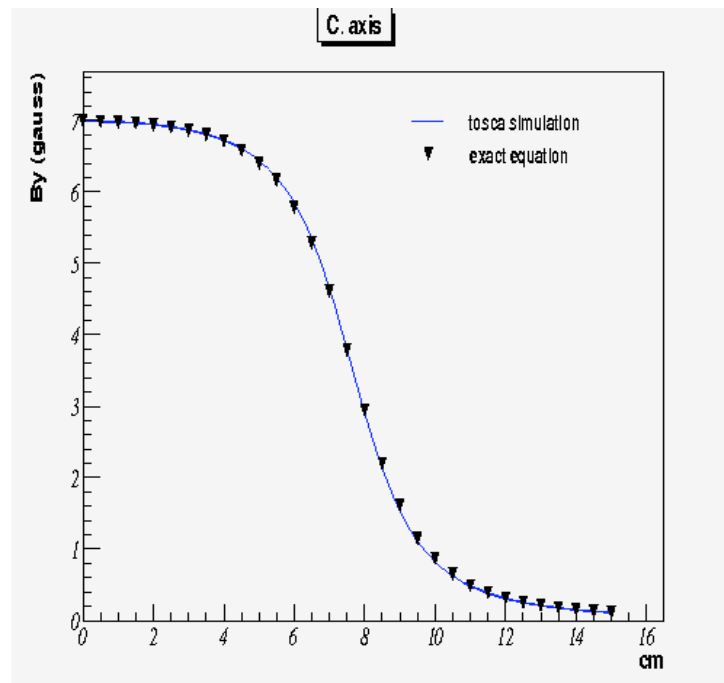
Layer thickness -- 0.24 mm

wire $D = 0.12 \text{ mm}$





- 1) The values were taken outside the solenoid, close to the wall and along the surface
- 2) "0"-point represents solenoid geometrical center
- 3) The approximate equation works better when solenoid length is much longer than radius. We can check



this fact from graph.

- 1) The values were taken on the central axis inside solenoid
- 2) The exact equation is independent of ratio between solenoid length and radius

Summary and conclusions on experimental studies of Holding Systems

- 1) Field map has been completed for the target of 1.5 cm diameter and 2.5 in length.
- 2) To make field mapping inside the solenoid we needed an axial probe.
- 3) In terms of increasing the target length both the simulations and mapping for a new holding magnet were done [10 cm target length]
- 4) We found that for the mapped bedstead system the 1 % homogeneity can be archived for a volume of 1.2 cm diameter and 4.3 cm in length.

- 5) To check how the holding system magnetic field can affect CLAS detector, the additional simulations for the both transversal and longitudinal geometry were done

Acknowledgments.

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